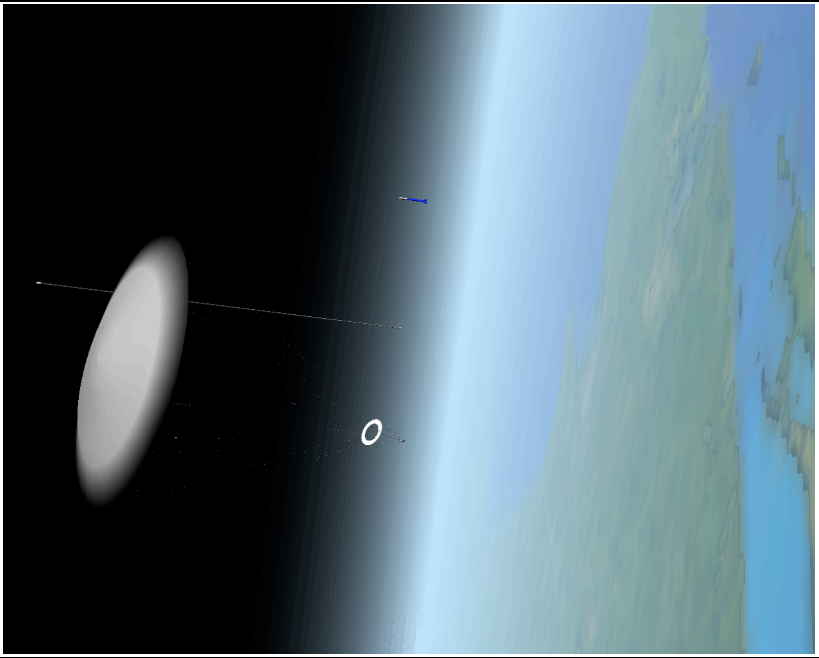

Advanced Projects Design Team – Team A

DRYDEN/JPL MEGACHUTE

Customer:
WENDELL RICKS
REVOLUTIONARY SYSTEMS CONCEPTS in AERONAUTICS

STUDY Leaders:
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Advanced Projects Design Team Report ID #X-807

July 12, 14, 15 2005

The Mega Mesospheric Parachute

Executive Summary

The current understanding and modeling of the upper reaches of the atmosphere is incomplete. Upper atmospheric interactions with the lower atmosphere, effects of ionizing radiation, high altitude cloud phenomena, and the dynamical interaction with the magnetosphere require greater definition.

The scientific objective of obtaining a greater understanding of the upper atmosphere can be achieved by designing, implementing, testing, and utilizing a facility that provides long period in-situ measurements of the mesosphere.

Current direct sub-sonic measurements of the upper atmosphere are hampered by the approximately one minute sub-sonic observation window of a ballistic sounding rocket regardless of the launch angle. In-situ measurements at greater than transonic speeds impart energy into the molecular atmospheric system and distort the true atmospheric chemistry. A long duration, sub-sonic capability will significantly enhance our ability to observe and measure:

- mesospheric lightning phenomena (sprites and blue jets)
- composition, structure and stratification of noctilucent clouds
- physics of seasonal radar echoes, gravity wave phenomena
- chemistry of mesospheric gaseous ratio mixing
- mesospheric interaction of ionizing radiation
- dynamic electric and magnetic fields

This new facility will also provide local field measurements which complement those that can be obtained through external measurements from satellite and ground-based platforms.

The 400 foot (~130 meter) diameter lightweight mega-mesospheric parachute system, deployed with a sounding rocket, is proposed herein as a method to increase sub-sonic mesospheric measurement time periods by more than an order of magnitude.

The report outlines a multi-year evolving science instrumentation suite in parallel with the development of the mega meso-chute facility. The developmental issues surrounding the meso-chute are chiefly materials selection (thermal and structural) and deployment mechanism physics.

Three mission cases were conceived and developed to include cost and schedules estimates. Each scenario has increasing scientific utility with paralleling launch weight, parachute hang-time, deployment altitude, and parachute size:

- Case #1: $8.4M@24 months, 6kg payload, 20 min., 50km alt., 80 m. dia.
- Case #2: $10.4M@24 months, 6kg payload, 20 min., 60km alt, 130m. dia.
- Case #3: $13.6M@36 months, 30kg payload, 30 min., 90km alt., 200m. dia.

The initial breakout cost for the parachute system is approximately $2M@24 months.

This report identifies that although the challenges of the mega-meso-chute may be difficult, they can be surmounted and valuable results can be achieved.

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1. Concept Summary

DISCLAIMER: SCOPING STUDY
This report described the work of a reduced-team study, considering very preliminary concept development for assessment of feasibility and key challenges. This was not a point design development.

This scoping study was carried out in collaboration between the NASA Dryden Flight Research Center and the Advanced Project Design Team at the NASA Jet Propulsion Laboratory.

The MegaChute concept is a new technology that would enable in-situ measurements of the Earth mesosphere for about 30x longer periods of time than currently possible. The concept is to deploy a gondola with science instruments, tracking and telecom capabilities under parachute sufficiently large to achieve subsonic speed as mesospheric altitudes (about 400-ft diameter). The gondola + parachute system would be launched to altitudes of up the 300,000-ft altitude by a sounding rocket, with the capability to float above 50-km for increasing durations up to about 30 min of in-situ science.

The goals of this Team A study were to:

- Refine the science objectives and measurement requirements of the mission,
- Develop a strawman science payload concept,
- Develop a design for the gondola,
- Capture the key parachute development challenges:
    - Parachute deployment,
    - Parachute stability,
    - Final descent guidance (or absence thereof)
- Assuming the parachute can be done, assess overall mission feasibility and estimate the cost of a realistic science program.

2. Science Plan (Earth Application)

DISCLAIMER: SCOPING STUDY
This plan is used for design sizing estimates only and is based on a brief survey of available literature. This is sufficient for delineating measurement classes, but does not define and prioritize measurement objectives.

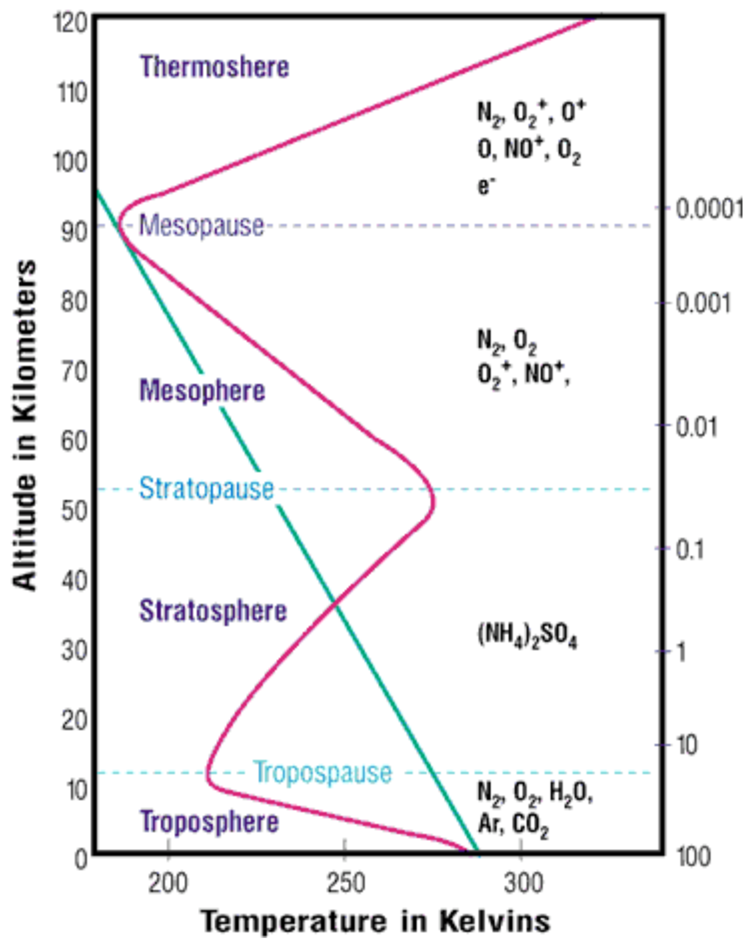


Figure 1 – Definition of Atmospheric Layers

2.1. Science Objectives

Science Objectives: Provide facility to measure mesosphere in-situ

The objective of the megachute program is to design, implement, test, and utilize a facility to provide in-situ measurements of the mesosphere. This capability is vital to measuring local field strengths, near-field chemistry, in-situ radiation environment, wave phenomena and stratification within the mesosphere. This new facility will provide measurements complementary to those that can be obtained through external measurements from satellite and ground-based platforms. The external measurements will in all cases provide superior temporal and spatial extent. The in-situ measurements will provide information on details such as layering, local fields, and short-lived (and/or short range) dynamic activity in the mesosphere.

Challenges for this facility include maximizing flight duration near the upper boundaries of the mesosphere, and deploying a large scale structure in this rather cold (-100C) environment. Prior experience has shown it to be very difficult to maintain velocities below mach 1 at altitudes higher than about 72 km.

This section is intended to provide background on extant mesospheric measurements and critical new measurements; an inventory of existing and planned satellite and ground facilities that provide opportunity for complementary science; a strawman science 10 year roadmap for exploring the mesosphere; and, critical for studying the feasibility of the megachute, a strawman set of instruments and instrument characteristics for a set of (phased) payloads.

Corollary: Complementary measurements with ground- and satellite-based capabilities

A sounding rocket and chute combination provides an unequalled capability to provide measurements of local and/or short-lived phenomena in the mesosphere. The measurement durations are short for this ~ ½ hour/flight. These measurements are most productive when made in conjunction with facilities that can measure greater extent or longer duration – specifically ground and satellite measurements optimized for the mesosphere. These measurements include LIDAR (which can locate noctilucent clouds and estimate the number of scatterers in the mesosphere), radar (which measures echoes from the mesosphere), low frequency radio (ELF and VLF), microwave limb sounders, and high speed imagers.

Mesospheric properties

Physical state

Table 1 – Physical stage of the mesosphere

Parameter	Value
Temperature Range	-100
Pressure Range	1-0.01 mbar
Stratopause	40 km
Mesopause	90 km
Particulates	Meteor ablation
Clouds	80-88 km
Atmosphere life	7 years

Composition

Mixing ratios are not constant in the upper mesosphere; this is an ongoing research topic. The figures 2, 3 and 4 provide background information on the composition of the mesosphere.

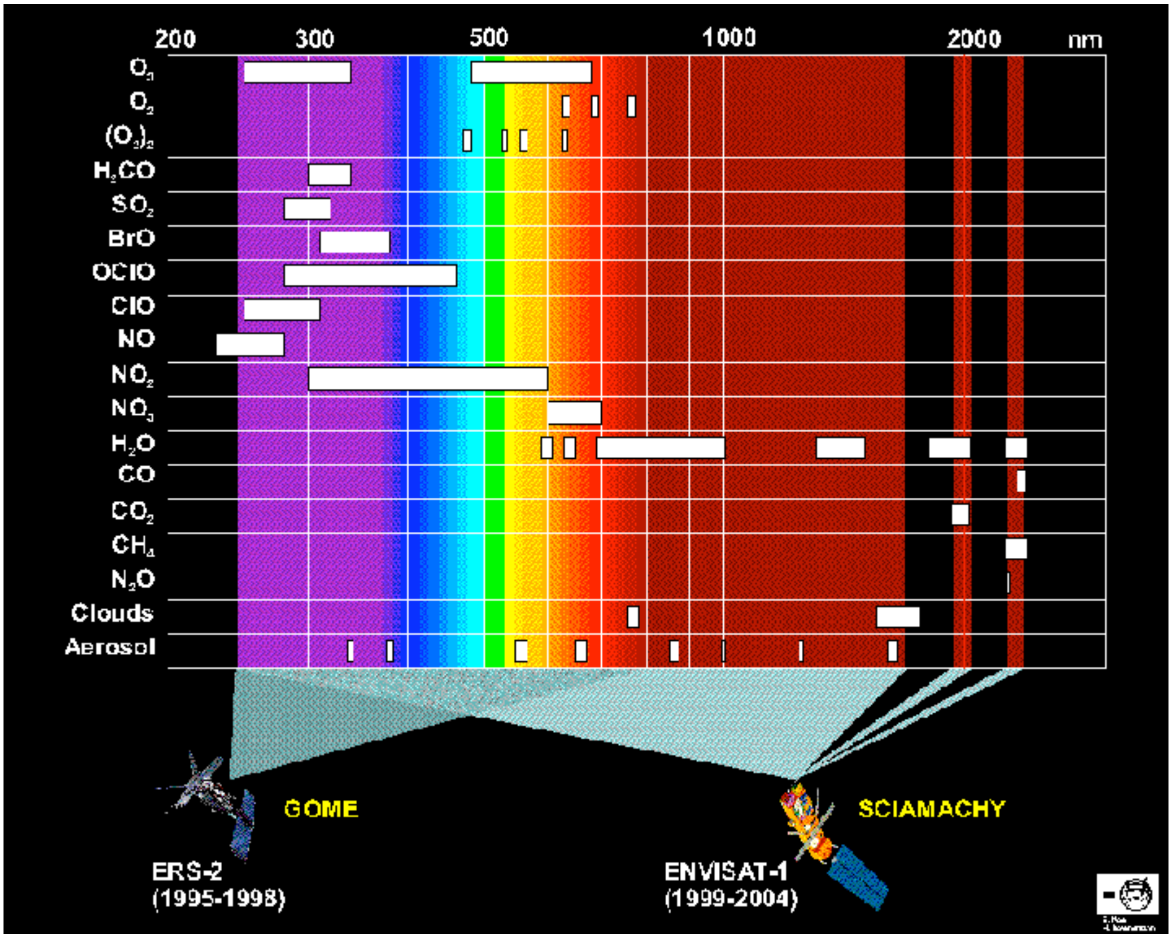


Figure 2 – Atmospheric Components measured by Satellite observations

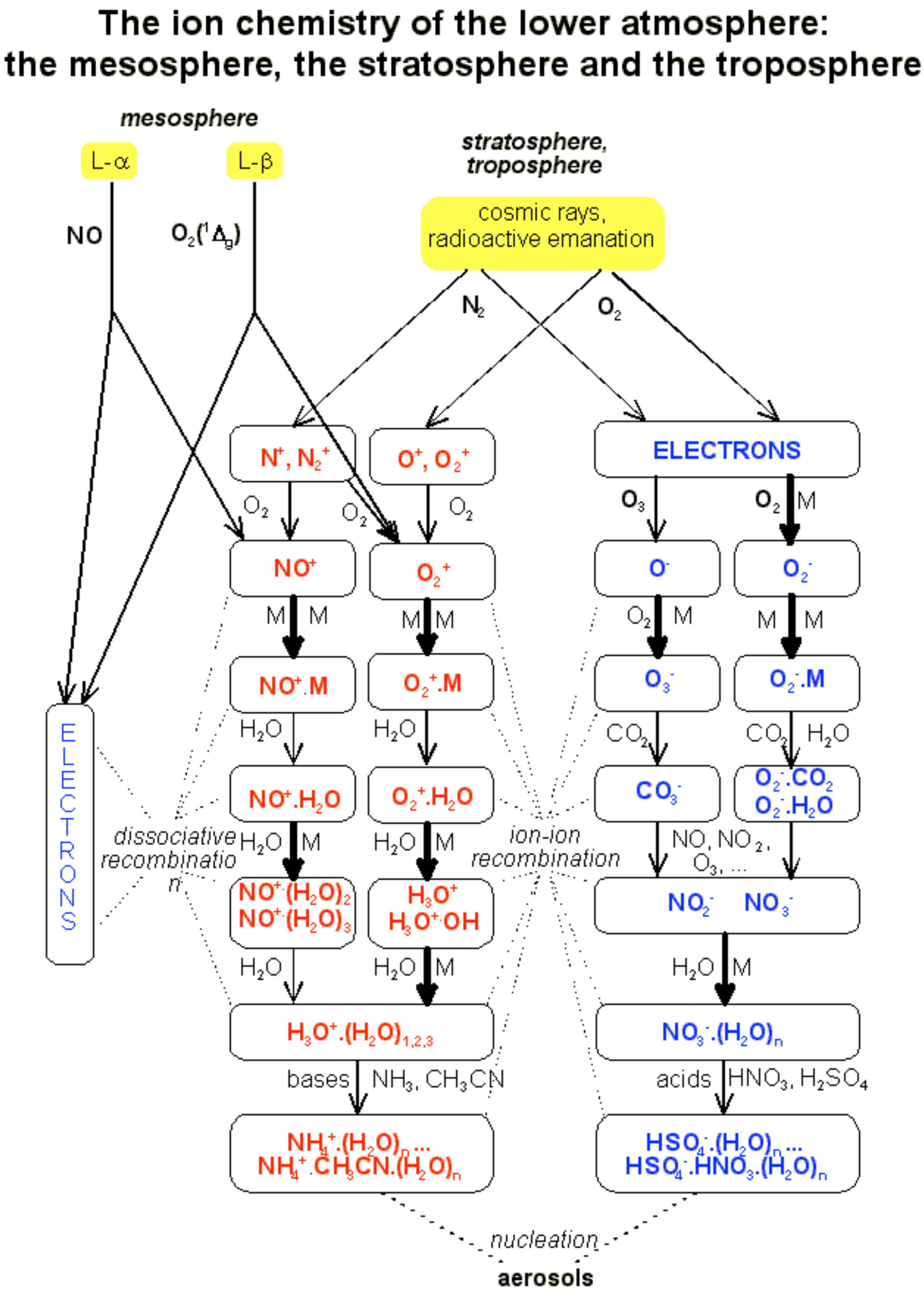


Figure 3 – Ion Chemistry of the Lower Atmosphere

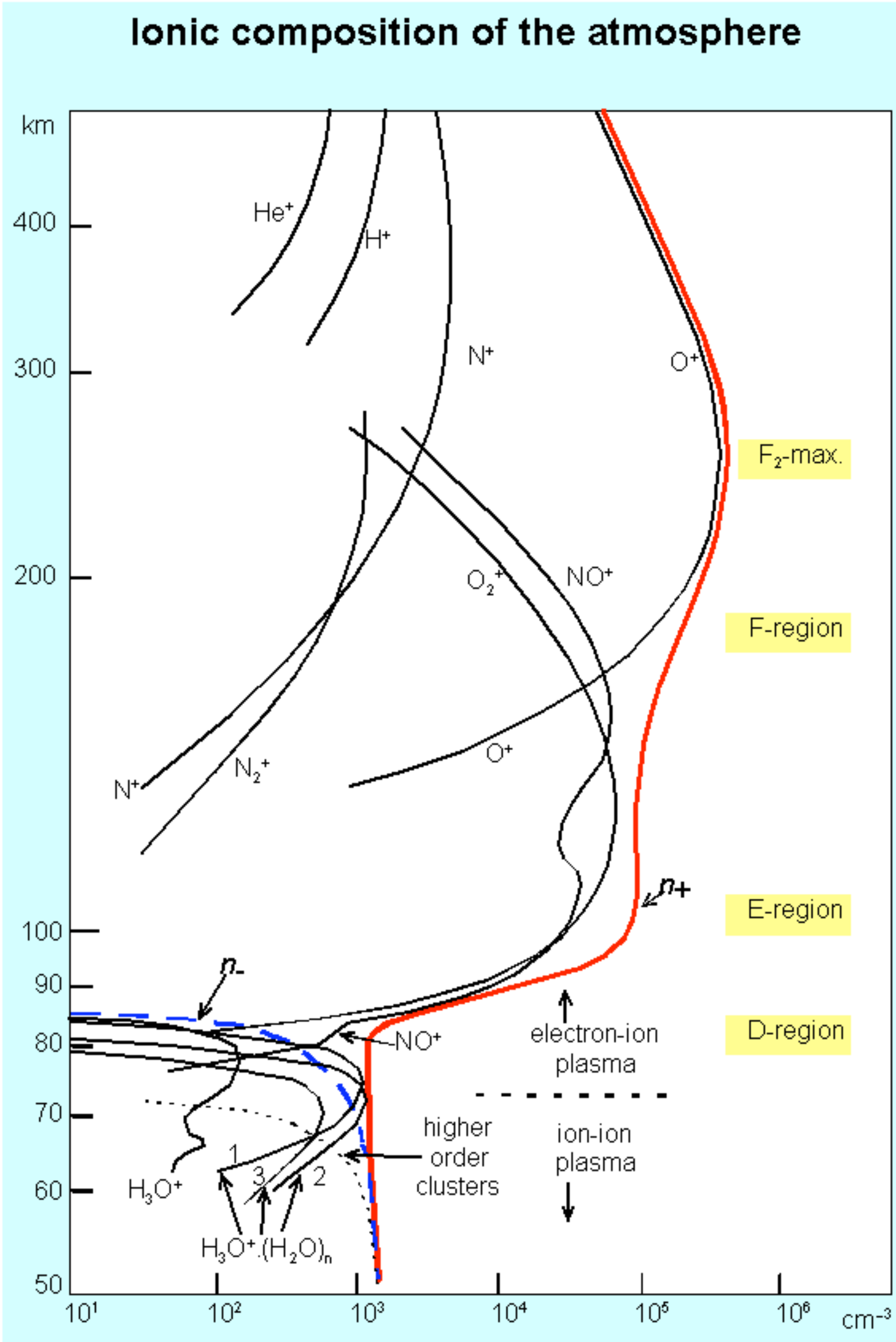


Figure 4 – Ionic Composition of the Lower Atmosphere

Transient activities

Sprites and waves are two transient activities of particular interest for mesospheric studies.

The table and pictures below provide background on the sprites phenomena, and the possibilities for sprite observation.

Table 2 – Sprite Phenomena Summary

Parameter	Value	Comments
Duration	1 ms-100 ms	
Frequency	1/minute (storm)	~2000 at any given time world-wide. Locations detectable in magnetic field
Extent	40x40x40 km(3)	
Locale	Florida, Africa, Japan, South America, Australia	Occur globally at mid and low latitudes

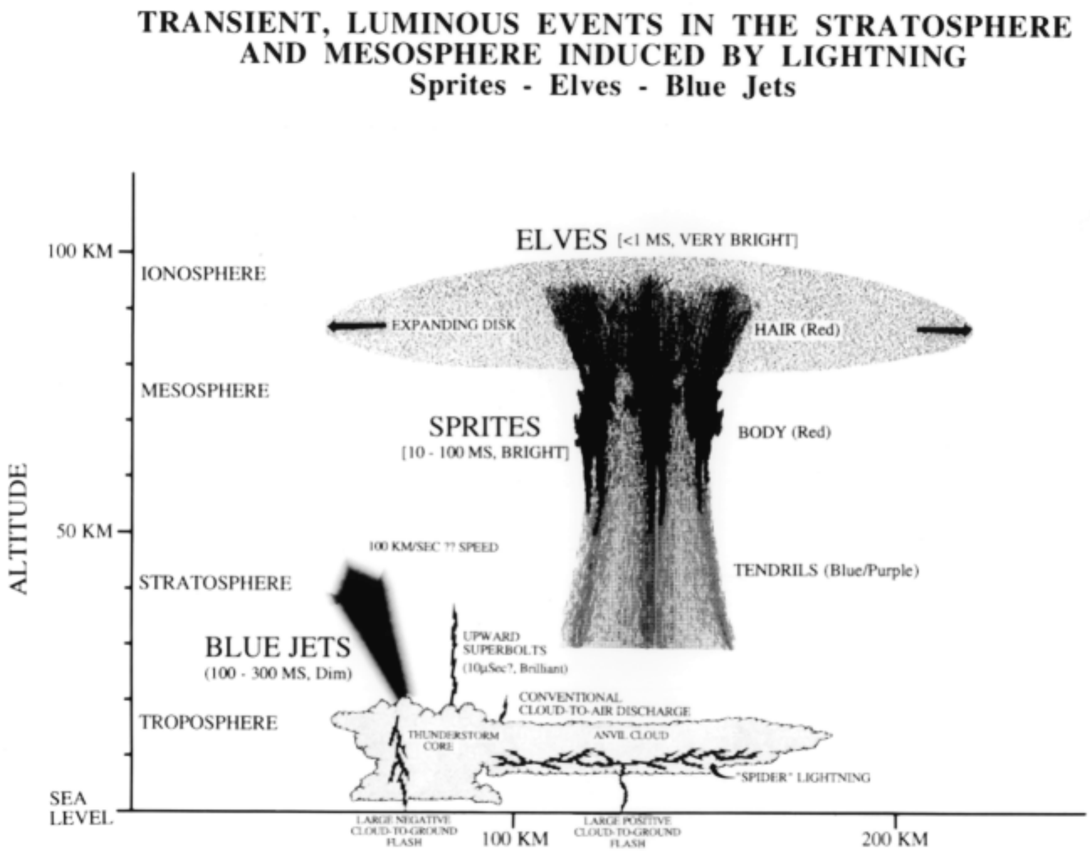


Figure 5 – Overview of Lightning-induced Events on Stratosphere and Mesosphere

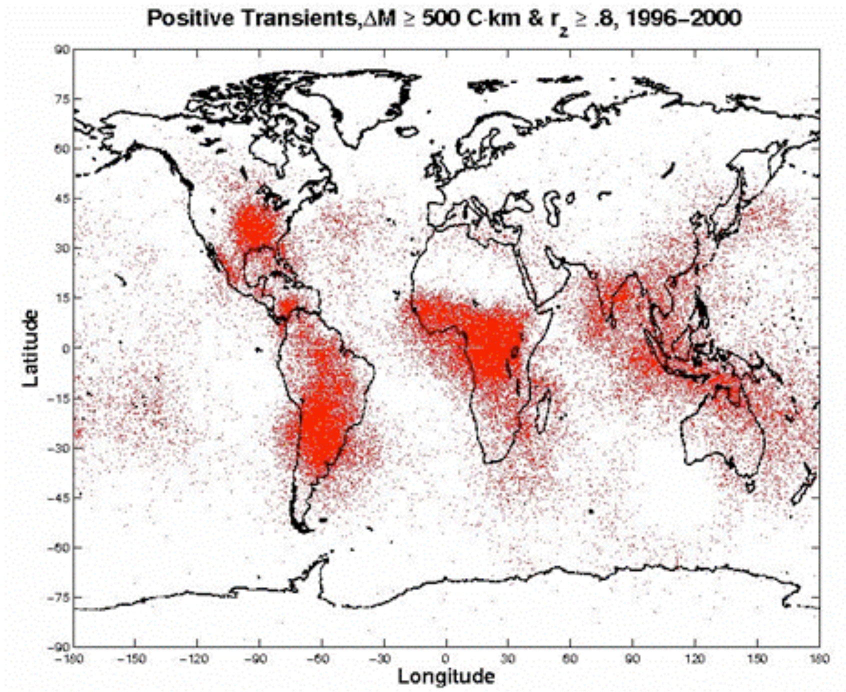


Figure 6 – World Map of Positive Transient Phenomena

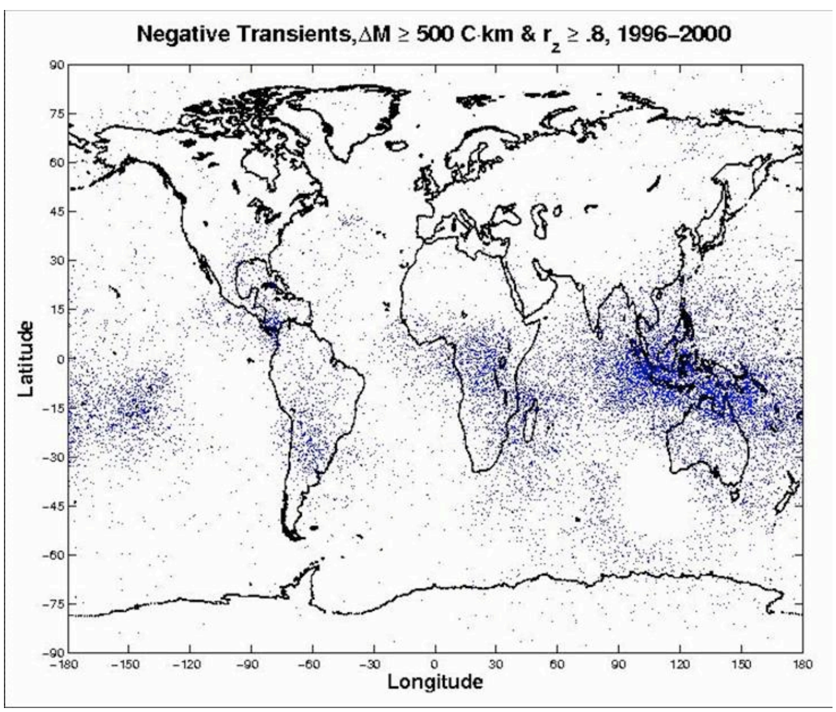


Figure 7 – World Map of Negative Transient Phenomena

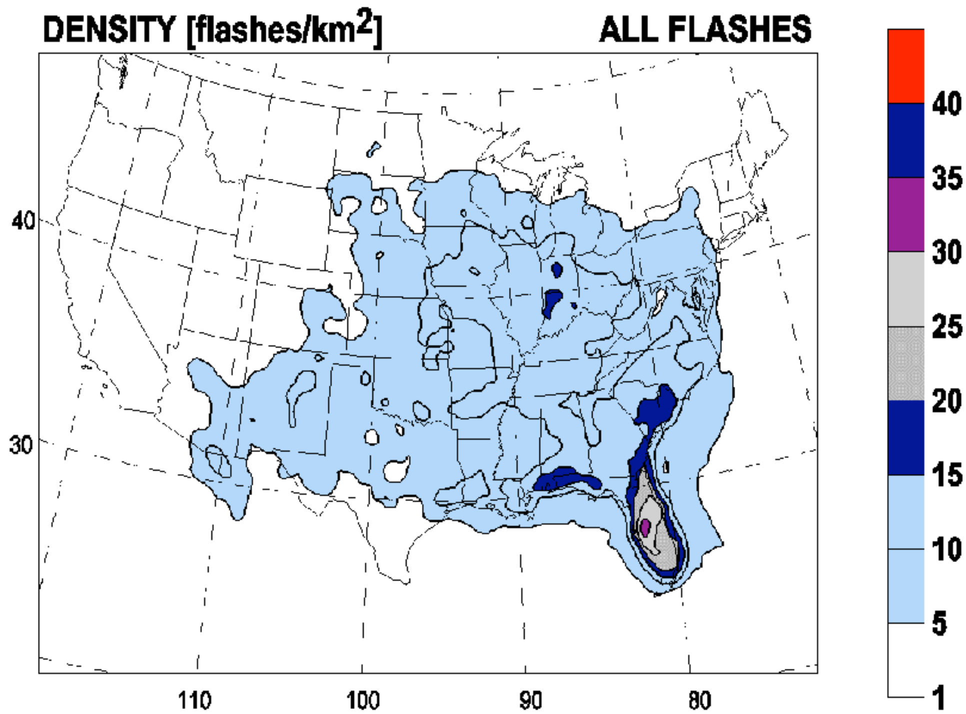


Figure 8 – US Map of Cloud-to-Ground Flashes Intensity

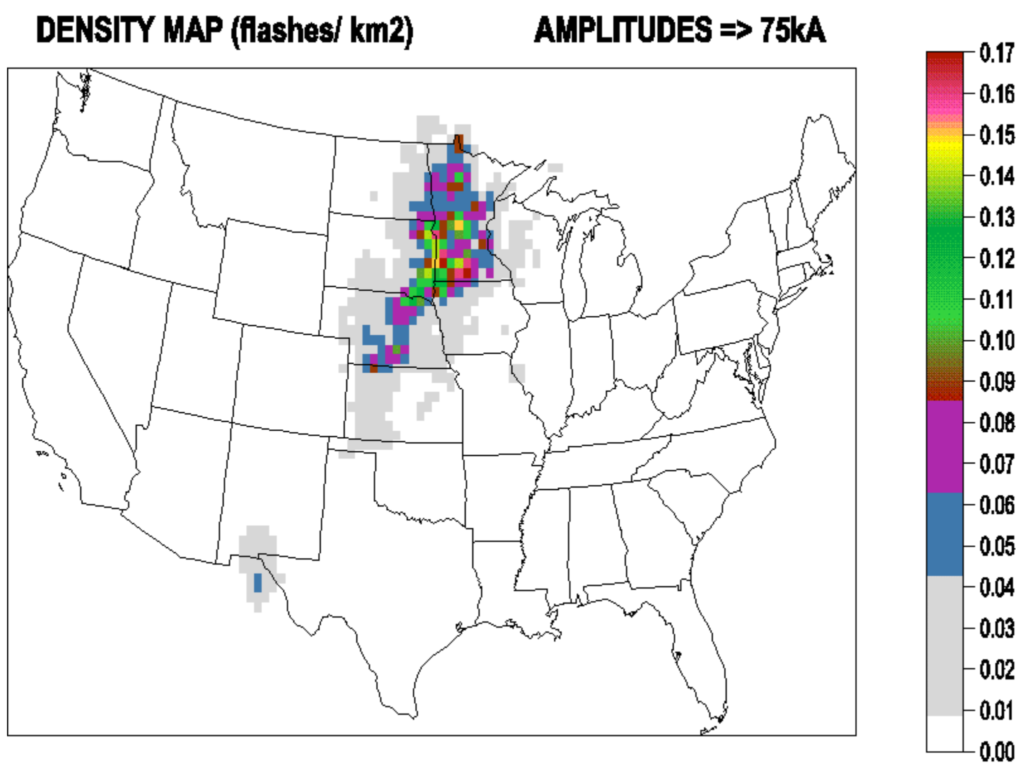


Figure 9 – US Map of Cloud-to-Ground Flashes of High Intensity

The measurement of waves is still to be surveyed.

2.2. Measurement Objectives

2.2.1. Past, present and future facilities & measurements

Current or planned facilities and measurements of the mesosphere include the following:

- High Plains Meteorite network
- Sounding: Poker Flat, Alaska, Scandinavian facilities
- Electric Field (ELF, VLF)
- Active and planned satellites, in particular:

Table 3 – Active and Planned Satellites of interest to Mesospheric Science

Name	Capability	Start Date	End Date	Comment
Earth Observing System, Aura	MLS - Microwave Limb Sounder	6/15/2004	~2011	Vertical atmospheric chemistry
FORMOSAT2	High-speed imaging of Mesospheric Lightning Events	5/20/2004	~2010	ISUAL - Imager of Sprites and Upper Atmospheric Lightnings.
CALIPSO /CloudSat/AIM	Noctilucent clouds	~2006	~2010	Mesospheric Clouds
UARS	Upper Atmosphere Research	1991	Still Operating	ozone chemistry and processes

- Near-term programs and campaigns, such as the International Polar Year. A web-based search yielded a quite a few named consortia, some, apparently, with as few as one member. Several examples of planned Earth Science missions are given at this website: http://www.nasa.gov/centers/goddard/missions/planned.html

2.2.2. Measurements Requirements

Assuming a series of megachute missions, not all measurements need to be made on all missions. A very interesting science program would make the following measurement over the multiple missions:

- ***Temperature, pressure, winds*** (all missions)
- ***Noctilucent clouds***. These clouds occur at about 80 km. It will be challenging to measure the layering in-situ because of the difficulty of achieving long hang times at this altitude.
- ***Summer/Winter (radar) echo***. The mechanism for the PWME is poorly understood.
- ***Sprites & Elves.*** Their occurrence is frequent ~ 1/minute during thunderstorms. Safety issues exist with respect to rocket operations during thunderstorms.
- ***Chemistry***. The mixing ratio is not constant in the upper mesosphere. The missions can contribute with a large number of new in-situ measurements to help understand the gradients and variability in upper mesospheric composition. Water may be generated in-situ.
- ***Dust***

- ***Meteorite dust.*** Significant amounts of K and Ca measured. The presence of these metals has been attributed to ablation of meteorites. The metal may coat ice grains and may participate in formation of sprites (though sprite formation moves upward…)

2.3. Strawman Science Payload

2.3.1. Instruments Requirements

The table below is a start at determining measurement performance requirements to meet the measurement objectives above. More work would be required to develop this into a full science traceability matrix for a mega-chute program.

Table 4 –Sample Measurement Performance Requirements

Instrument	Parameter	Range
Barometer	Pressure	0.001 – 10 mbar
Thermometer	Temperature	-120 - -70 C
Nephelometer	Scattering	
GPS	Winds	
Radiometer(s)	Insulation	
Extremely Low Frequency		3-3khz
Very Low Freq.		3-30khz
Ultrasound		?
LIDAR		40 km range
Ext Ultra Violet		
Infra Red		
High Speed Camera		1 ms for 60 sec (focal plane storage

Environment: Barometer, Thermometer, GPS

- A Global Positioning System (GPS) receiver is part of the gondola avionics for tracking of the megachute vehicle. This measurement will also have science value, in particular in the study of winds.
- Thermometry may be difficult in the rarefied flow environment. Temperature at these altitudes is normally measured as a rotation temperature for some gas. At 0.01 millibar, traditional resistance thermometers may not work well – thus temperature sensors would be more complex than usually used. This requires further study.
- For pressure, standard low pressure strain gauge barometers may be used.

ELF, VLF, Radar

The design of the system assumes that ELF and radar antennas can be incorporated as part of the very long (>~150 meter) support lines. This would provide the large baseline required for these measurements.

Filter Photometers, all-sky cameras

Given that the observation of sprites in not guaranteed, an all sky camera should be included on most flights to improve sprite statistics. That camera must have relatively high speed.

LIDAR

Ground LIDAR is required to locate noctilucent clouds with vertical view. Scanning LIDAR, and, perhaps, acoustic sounders would be appropriate instruments for cloud and particulate studies. Ranges are relatively short (vertical extent ~50 km), so a scanning LIDAR may be feasible.

Ion spectrometer, Low energy particles

Ionized species play a large role in mesospheric chemistry. In-situ measurements of these would doubtlessly provide new understanding of the kinetics and reaction pathways for this chemistry.

Conductivity

Conductivity measurements might be possible utilizing the support lines (shrouds).

2.3.2. Phased Program

Strategy

The science Program for the mega-chute should be phased to introduce increasing capability in two main challenging areas:

1. Increasing height: The density at the mesopause is sufficiently low (approximately 0.01 millibar) to pose extreme engineering challenges. This improves below about 70 km.
2. Stricter temporal requirements: The program moves from generic to time-critical events. Time criticality arises from transient atmospheric events (e.g. sprites), satellite view periods (trying to time the in-situ megachute measurements with a satellite overpass), or both.

A good ten year program would be divided into 4 major campaigns, increasing in experimental difficulty, as outlined below. The goals of this phasing would be to have minimal mass payloads for the testing and high altitude phases, and a minimum incremental cost issue.

It is recommended to associate most flights with significant ground and satellite program collaborative measurements. This would greatly improve the correlative science and temporal extent for chute measurements.

Phase A: Test and integration

A light package and relatively inexpensive payload should be used during development and test. The first missions are envisioned to reach the 40 km – 60 km altitude range as a first demonstration of the megachute concept.

Phase B: Low mesosphere measurements

Measurements at altitudes below 70 km are considered more obtainable from a parachute engineering point of view. Flight durations of 10-20 minutes in this region should be adequate to support a wide range of in-situ measurements.

Phase C: Measurements of transient phenomena

This is considered "best science value" is kept for the later phase of the program, when full mega-chute technology development provides access to the full 50 km – 90 km altitude range for durations of close to 30-min. While observation of sprites would be a high scientific interest, it will be difficult to coordinate measurements of sprites with satellite view periods.

Phase D: Upper mesosphere measurements

Upper mesospheric measurements are extremely difficult because of the low atmospheric density, and extremely valuable because of the paucity of measurements that can define activity in the region of the mesopause. This is also considered "best science value" is kept for the later phase of the program, when full mega-chute technology development provides access to the full 50 km – 90 km altitude range for durations getting close to 30-min.

Instrument descriptions

Mass, Power, sample rate, data

Estimates of sample rates and data rates are reasonably accurate. They are closely related to the measurement requirements, i.e. the parameters being measured.

The mass and power estimates that we developed for this study are less reliable, due to the short time available to locate suitable instrumentation. It should be noted that instruments mounted on airship and satellite platforms, performing similar measurements from a much greater range, consume an order of magnitude (or worse) greater mass and power resources.

Instrument heritage

- Instrument heritage (for this report) is minimal because of the brief and exploratory nature of the study. Instrument characteristics were estimated from similar trade-show instruments descriptions and from Mars and deep space flight instruments. It was assumed that the space-flight instruments can be converted to (lighter and much less expensive) rocket flight instruments.
- Non-Recurring Engineering (NRE) costs were not included in the instrument cost estimates. If these instruments are not being developed elsewhere, this can be a significant caveat for the study, as NRE can run as high as several $Million per instrument development.

Table 5 below summarizes the phase science payload approach. It is also available in Excel format.

Table 5 – Strawman Payload for Phased Science Approach

Strawman Instrument Specifications						Phase Science Program			
Instrument	Objective	Cost (no NRE)	Mass	Power	Data Rate	A - 24 months	B - 24 months	C - 36 months	D - 36 months
		$K	kg	W	kpbs	60 km	60 km	70 km	90 km
Temperature	Lapse rate, energy depostion	5	0.1	0.1	1	1	1	1	1
Pressure	Lapse rate, mixing ratio	5	0.1	0.1	1	1	1	1	1
Radar	PMWE, PMSE, Metals	50	5	20	400		1	1	1
ELF/VLF	Sprites	75	5	3	20	1	1	1	
LIDAR	PMWE, PMSE	150	8	20	2		1		1
X-Ray	Energetic Processes	75	6	5	2				
UV-IR	Chemistry, Temperature, Particulates, waves	400	7	10	400		1	1	1
Laser Spectrometer	Chemistry, kinetics	250	2	2	20		1		1
High-speed camera	Sprites	200	3	30	1000		1		1
Femptowatt Photometer	Potassium, Calcium	150	3	5	4		1	1	
Kev and Neutral	Low speed ions, energetics	150	6	7	2			1	
MEV	High speed ions	150	8	8	2			1	
Magnetometer	Sprites, ion population	20	0.5	1	2		1	1	1
Microwave	Chemistry, isotopes, waves	100	10	5	2			1	
Nephelometer/ Scatterometer	Particulates	50	4	2	1		1		
TOF mass spec	Metals	60	4	5	3				1
Radiometer	Energy balance	10	1	1	1	1	1	1	
Subtotal			**72.5**	**124**	**1861**				
					Total Mass (kg)	**6**	**38.5**	**45.5**	**29.5**
					Total Power (W)	**4**	**94**	**60**	**88**
					Total Data Rate (kbps)	**21**	**1850**	**833**	**1827**
					Total Cost without NRE ($K)	**85**	**1355**	**1105**	**1130**
					Total Data Volume (bits)	**2.52E+07**	**2.22E+09**	**1.00E+09**	**2.19E+09**
					Science Targets	Integration / Test	Mesopause - in-situ	Transients	Mesopause - in-situ
						Chemistry / Winds	Noctilucent clouds	Sprites	Noctilucent layering
									Meteoric chemistry

Assumes: *28 volt bus, instrument costs without NRE, all instrument parameters wags based on trade show data and/or deep space instruments*
Mass and power estimates include no contingency. Add 30% for payload mass margin

2.4. References

A folder of (web-derived) reference material was developed on the JPL Advanced Studies Design Team server, and can be made available to customers on-demand.

3. Gondola Design and Mass Summaries

3.1. System Guidelines and Assumptions

Design guidelines

In addition to the strawman science plan, Team A developed:

- A preliminary designs for possible gondola systems that respond to the phase science plan, so as to define realistic payload masses for the megachute, and
- A strawman mass budget for the whole gondola+megachute system, as part of feasibility assessment for the mission concept.

Team A used the following design guidelines in developing these products:

- All gondola systems need to be at a Technology Readiness Level (TRL) of 6 today. In an effort to control cost and risk, all new technology developments will be focused on the megachute concept.
- The design for the vehicle follows JPL's Design Principles with regards to mass and power contingency. These principles require a 2% contingency on mass for existing hardware, 10-15% contingency on mass for an inherited design and 30% contingency on mass for a new design. In addition, additional contingency has been added above that to reach a total of 30% growth contingency in both mass and power. This contingency method is under review, but Team X has a working agreement with the owner of JPL's Design Principles to use this method until further notice.
- For very new technology with no heritage, 50% growth contingency is suggested. This number was used here for the mega-chute system mass estimates, with the exception of the mega-chute itself. The mega-chute was treated as a mass allocation for a given diameter. This allocation would need to be the target of the parachute technology development.

Design assumptions

In addition, the design relies on the following assumptions:

- Commercial-off-the-shelf (COTS) parts can be used for the gondola design, with minor qualification required to verify performance in the rarefied flow environment of the upper mesosphere. No space-qualified parts are required. The use of space-qualified parts would significantly increase the mass of the gondola system.
- Per FAA requirements, the gondola+megachute vehicle needs to be tracked from the ground even in case of mission anomaly. This requires carrying an FAA-compliant transponder in addition to the baseline positioning and telecom capabilities of the vehicle.
- The Wallops launch range has a preference for guided vehicle, which can guarantee their stay on-range of the facilities. This was not considered a requirement for all design Cases.
- Steering algorithms exist for parafoil systems, which can land within 2 m of the target, except if the winds are sufficient to make the chute drift beyond the control authority of the vehicle. Similar algorithms could be used to guide a megachute system.

3.2. *System Description and Mass Budget*

3.2.1. Summary of considered mission cases

Out of a number of possible gondola and megachute designs likely to be used during a phased, multi-mission megachute program, the Team considered three design cases:

1. Case 1 is considered "minimum science" case, to be used during the first megachute development missions. This case explores only the lower mesosphere with a launch at 75 km, carrying a minimum instrument package. This case separates the megachute at about 40 km, and proceeds with passive descent without any guidance or recovery.
2. Case 2, although still carrying a minimum science package, would make two significant improvements in capability: it would explore the whole mesosphere with a launch to 100 km; and it would include guidance while on the megachute, followed by fast descent on drogue chute, and opening of a terminal descent parafoil, allowing mid-air recovery of the whole gondola.
3. Case 3 is considered the "best science value" case. To the altitude, guidance and recovery capabilities of Case 2, mass capability would be added to deliver a comprehensive science package and carry out a full-science, 30-min long mission through the whole mesosphere.

The key characteristics of these cases are summarized in the table below.

Table 6 – Summary of Design Cases Considered in the Study

<table>
<tr><th></th><th>Case 1 (minimum)</th><th>Case 2 (guided)</th><th>Case 3 (full)</th></tr>
<tr><td colspan="4">Requirements</td></tr>
<tr><td>Science payload</td><td><u>Minimum (Science Phase A):</u>
• ELF/VLF
• Temperature
• Pressure</td><td><u>Minimum (Science Phase A):</u>
• ELF/VLF
• Temperature
Pressure</td><td><u>Best Value (Science Phase D):</u>
• Radar
• LIDAR
• Laser spectrometer
• TOF mass spec.
• UV/IR
• High-speed camera
• Magnetometer
• Temperature
• Pressure</td></tr>
<tr><td>Science altitude</td><td>20 min @ 60 km – 40 km</td><td>20 min @ 60 km – 40 km</td><td>30 min @ 90 – 50 km</td></tr>
<tr><td>Launch altitude</td><td>~75 km</td><td>~100 km</td><td>~100 km</td></tr>
<tr><td>Final descent</td><td>Tracking -- No guidance</td><td>Tracking & Guidance</td><td>Tracking & Guidance</td></tr>
<tr><td>Landing & Recovery</td><td>Ocean -- No recovery</td><td>Mid-air retrieval</td><td>Mid-air retrieval</td></tr>
<tr><td colspan="4">Results</td></tr>
<tr><td>Science payload</td><td>6 kg CBE</td><td>6 kg CBE</td><td>30 kg CBE</td></tr>
<tr><td rowspan="2">Gondola total mass</td><td>38 kg</td><td>41 kg</td><td>90 kg</td></tr>
<tr><td colspan="3">includes 30% contingency</td></tr>
<tr><td rowspan="2">Final descent system</td><td>0 kg</td><td>45 kg</td><td>100 kg</td></tr>
<tr><td colspan="3">includes 30% contingency</td></tr>
<tr><td>Mega-chute diameter</td><td>~80 m</td><td>~130 m</td><td>~200 m</td></tr>
<tr><td rowspan="2">Mega-chute system</td><td>~330 kg</td><td>~675 kg</td><td>~1400 kg</td></tr>
<tr><td colspan="3">includes 50% contingency on all but mega-chute, treated as allocation</td></tr>
<tr><td>Total launch mass</td><td>~365 kg</td><td>~760 kg</td><td>~1600 kg</td></tr>
<tr><td>Launch vehicle</td><td>Terrier-Orion</td><td>Terrier-Black Brant IV</td><td>Terrier-Black Brant XI</td></tr>
<tr><td>Launch margin</td><td>0-10%</td><td>~20%</td><td>< -50%</td></tr>
</table>

3.2.2. Case 1: first application

Gondola Design

Attitude Determination and Control System (ADCS)

The same position determination and attitude determination subsystem is carried in the gondola for all Cases.

For all Cases, knowledge of position and orientation during the flight is required for science. Position determination within an error radius of 20 meters (3 sigma) should be sufficient. Knowledge of instrument bench orientation (on the gondola) within about 1 degree (3 sigma) should be sufficient. This would apply to the RSS of uncertainty in two axes, so would correspond to per-axis knowledge within ±0.707 degrees (3 sigma).

There is also a requirement to observe the chute deployment for all Cases. Video cameras are included in the ADCS equipment list for this purpose.

- Position would be determined using a micro-GPS device.
- The baseline includes a 50-gram, 1 Watt, non-space-qualified unit that would be integrated with the rest of the avionics. The cost of the device was assumed to be low (e.g., < $10K).
- The assumption is that the micro-GPS would use P-code to provide real-time accuracy to within a 3-sigma error radius of 20 meters, throughout the flight.
- Onboard attitude determination would be based on precision gyros in an Inertial Measurement Unit (IMU) and coarse analog sun sensors mounted on the sides of the gondola.
- IMU would be a Litton LN-200S containing three fiber optic gyros (FOG's). Non-space-qualified version that costs $110K (compared with $220K for space-qualified). Mass of 0.75 kg, 12 Watts power, single axis, 1-sigma accuracy within ±0.35 deg/hour.
- Non-space-qualified LN-200S is designed for aircraft flying at altitudes of up to 50,000 ft, so could introduce additional risk using it at considerably higher altitudes. Fallback would be to pay $220K for space-qualified unit.
- Note that current technology micro-electromechanical system (MEMS) gyros have lower mass and cost less, but do not have the accuracy to support 1-degree knowledge during a flight of tens of minutes. For instance, the Draper MEMS gyro package would be around 300 grams and might require 2 to 4 Watts, but the gyro drift could be as high as 10 degrees/hour.
- A set of four coarse analog sun sensors would provide some additional information that could be used to estimate gyro drift/calibrate the gyros during attitude reconstruction on Earth (post-flight). About 5 grams apiece, virtually no power, and a cost of < $10K apiece.
- Four video cameras offer various look angles at the megachute above the gondola. Their main function is to capture the whole megachute deployment sequence, a critical piece of information for further technology development and design. This data needs to be relayed in real time in case the mission does not perform as planned.
- Information from the video cameras, position and attitude sensors can be used to reconstruct winds, refine parachute drag coefficient estimates, and understand parachute stability problems.

Command and Data Handling System (CDS)

A small command and data handling system (CDS) is required to tie in the data streams from the various science instruments and ACS sensors into one integrated downlink to the ground station. In the absence of an avionics chair, a placeholder mass of 0.5 kg and power level of 5 W were used. This is considered an adequate placeholder for non-space-qualified parts.

Telecom

Since Case 1 has no capability for recovery, a Telecom subsystem is required on the gondola to relay all positioning, attitude and instrument data to the ground. Real-time relay is preferred so as to limit data processing, buffering and play-back requirements on the CDS.

- The typical range of the sounding rockets is less then 100 km for launch to 100 km altitude. However, drift on the mega-chute is also expected, especially for this unguided Case 1. For this reason, the telecom link was designed for a range of up to 200-km from the ground base.
- The video cameras filming the megachute deployment are the key driver for the Telecom data rate, requiring a constant 60 Mbps downlink to the ground station. This is achieved with a small UHF transmitter and a UHF line antenna. Although the system required 40 W of input power, it is on only during the main mega-chute descent, leading to small energy requirements.

In addition, a tracking transponder and an S-band omni-directional antenna are also carried on board the gondola to meet the assumed FAA requirements. Their mass was estimated by analogy with similar systems on balloon missions.

Design Requirements:

- Support a downlink of 60 Mbps from a range of 200 km
- After short duration at 60 Mbps, transmit at lower data rate
- Single string design
- Commercial (not space) equipment
- Must carry an FAA transponder and antenna
- 10 dB margin on downlink

Design Assumptions:

- Will use UHF Ham radio band for transmitting data down to small ground antenna
- Will use a UHF Yagi antenna (20 dBi) for receiving signal from chute. The antenna can manually steer towards the chute.
- The link is uncoded.
- This is a line of sight, direct link between the megachute gondola and the grounds station.

Design:

- Design has one commercial UHF transmitter with 5W power amplifier and a horizontal linear UHF monopole antenna, one FAA transponder with antenna, cabling
- Based on conversation with Viktor Kerzhanovich, the UHF transmitter can be very cheap commercial unit with very simple UHF antenna. The mission will also have to purchase the ground antenna and receiver. Viktor's transmitters were a lower data rate – video signal using AM- and had a 1W amplifier. Increasing the power to 5W should not be a problem.
- In the limited time available, only nominal value were used for the FAA transponder and antenna mass and power. The transponder is on all of the time.

Telecom Subsystem Trades.

- The mission may consider using hardware at a different band (L or S). Future work could investigate the frequency allocation available for this type of experiment and bandwidth required for 60 Mbps. Could the mission get a higher gain ground antenna to lower the power for the transmitter?
- Adding a simple convolutional code could reduce the transmit power.

Telecom Subsystem Cost

The total, rough estimate is less than $50K including a few days of labor assembling the hardware.

Power

The instrument and attitude sensors, as well as the CDS and Telecom subsystems, are to be supported by a primary battery system.

- 190 W-hr are sufficient to power the gondola through launch and deployment, up to 30-min of science, an up to 3-hours of final descent. This final descent phase can be considered energy margin in case further tracking and downlink are desired in that phase, at least for anomaly tracking after megachute release. This energy is provided by an LiSOCl2 primary battery, which are well known to perform favorably in mildly cold temperatures and have been used on many missions. The cost of these batteries is not expected to be excessive.
- The Power subsystem also includes the power electronics required to load-level and distribute the battery power to the various instruments and subsystems: load switching, battery control and diode boards.
- It may be advantageous to examine the utility of a point-of-use, distributed power system, where several smaller, battery are used to power individual subsystems. This design would increase fault tolerance without any significant mass penalty. The costs of designing and implementing a larger power bus and PMAD system might also be avoided.

Thermal

The thermal design of the gondola was not considered. In the absence of any special thermal requirement for the instruments, the thermal subsystem would simply include passive insulation surfaces as well as thermal sensors. Typical sizing equations were used to estimate their masses in the absence of a Thermal subsystem engineer.

Structures

Structural mass

Although the gondola should be similar to previous designs, no typical MEL (Mass and Equipment List) was available. Thus, the structure mass was estimated parametrically using the TeamX linked estimating tools.

- These tools base the major structure mass on the masses of the other subsystems which the structure supports, plus specific identified substructures, components and mechanisms.
- Cabling harness mass estimate is based on historical factors times the mass of the separate electrically connected subsystems and mechanisms. Since mass is so critical in these missions, an assumption was made for direct connection of all wiring, saving the mass of most connectors. Cabling mass always seems high, but the reality is that the cabling harness mass is historically under-estimated by projects.

Structures and Mechanisms equipment list (including cabling harness) and mass tables are compiled with the other subsystems lists in the Systems tables below. Theses masses include only what is needed on the gondola. Any structural appendages required for stowing, deploying and controlling the megachute is assumed part of the megachute mass allocation.

An accurate structural mass estimate would require further analysis of the launch loads and launch configuration, stowing and deployment devices, as well as physical sizing of the gondola package.

Redundancy and compliance with JPL Design Guidelines

Structure by its very nature can never be redundant, but mechanisms will have redundant actuators or dual motor windings in order to achieve single-fault tolerance. Bus structure and mechanisms are almost always new specific designs and thus should be set at 30% mass contingency, in accordance with JPL design guidelines. Cabling harness should also carry 30% mass contingency

Structures cost

This is not a space mission. Instead, this mission is similar to balloon missions in workforce and QA approach. In consideration of this, the costs are estimated as much lower than they would be for even a Class D space mission. There is also no cost allowance for any spares.

- The Structure/Mechanical subsystem (structures, mechanisms, and cabling harness) cost for the Case 1 and 2 Gondola totals $K450 for non-recurring, $K230 for recurring, = $K680 total. The mechanical I+T cost is $K120 for non-recurring and $K70 for recurring, or $K190 total.
- The Structure/Mechanical subsystem (structures, mechanisms, and cabling harness) cost for the Case 3 Gondola totals $K650 for non-recurring, $K320 for recurring, = $K980 total. The mechanical I+T cost is $K140s for non-recurring and $K80 for recurring, or $K210 total.
- The Recurring cost is the cost of building a set of flight hardware after all engineering and development have been completed; it consists of 85% of the flight hardware, some engineering costs, and the qual. testing. The Non-Recurring costs include most of the engineering, the development testing, 15% of the flight hardware, and spares. The sum of the two categories is the cost of designing and building the first flight unit.
- The Mechanical I&T costs are the mechanical portion of what have traditionally been called Systems ATLO (assembly, test, and launch operations) costs.

Open issues and future work

Future work should give a close look at how the mega-chute and gondola will interface with the launch vehicle. While it is easy enough to estimate the mass of the gondola, the parachute housings and deployment sequencing devices, and the adapter/staging hardware have not been considered in this study. These topics are important to the overall mission, and need to be considered in future work.

Vehicle Mass Budget

The gondola design results in a total gondola mass of about 30 kg current-best-estimate (CBE), or 38 kg with 30% mass contingency.

Since Case 1 does not include any recovery, no final descent system is needed. The gondola mass of 38 kg represents the payload mass for the megachute system.

Very preliminary estimates for the megachute system where developed for the purpose of assessing feasibility and developing parachute mass allocations. The mass for each main element of the system is summarized on the system sheets below. They are:

- The mega-chute itself, for which only a mass allocation was developed. A chute of about 80-m diameter is estimated to be required to achieve subsonic speeds at 60-km altitude with a 38-kg payload. The parachute aerial density can vary widely based on material choice and design assumptions, and won't be known until further technology development progress. However, a representative mass estimate of 220 kg was provided by the parachute design experts for this case, for the total mass of the canopy and suspension lines. This provides an allocation that is both within the realm of possible technological achievements, and feasible within sounding rocket capabilities. **No mass contingency was carried on this item, which is considered an allocation for technology development tasks.**
- An inflatable pneumatic ring and pneumatic tub stalk. Placed by the stalk above the gondola at a fraction (1/10) of the distance to the parachute, and only a fraction (1/10) of the parachute diameter, this ring would provide an air inlet to help with parachute deployment, following similar concept currently used for conventional parachutes. The mass estimates for the ring, stalk, and their inflation system were developed by analogy with airbag systems, which have similar fast inflation requirements. These items carry a mass contingency of 50%, due to the very preliminary nature of the concept.

These estimates result in a total floated mass of 290 kg on the megachute, and a total launch mass inside the sounding rocket of 365 kg. The volume of the stowed mega-chute alone is estimated to be about 1/3 m^3.

Mass & Power Summary Sheets

- The system sheets for Case 1 are shown on the following pages. These sheets include study guidelines and assumptions, the system worksheets and the equipment lists for the MegaChute vehicle.
- Note that contingency is book-kept in two separate ways on the system sheet. Subsystem contingency is added at the component level. In addition, system level contingency is the amount of mass required to reach a total mass contingency of 30% on the gondola system.
- The margins on the bottom of the sheet are against the CBE+Contingency Mass. The Launch Vehicle Margin % is against the launch vehicle mass allocation. The Spacecraft Margin % is against the current CBE+Contingency. Note that there is no contingency taken against the launch vehicle.

Table 7 – System Guidelines for the Mega-Chute, Case 1

Team X Study Guidelines

Dryden MegaChute - Case 1 - Minimum Science Mission

	Programmatics/Mission
Customer	Kurt Kloesel
Study Lead	Bob Oberto / Bob Kinsey
Mission	MegaChute (Dryden)
Target Body	Earth mesosphere
Trajectory	Launch by sounding rocket to ~75 km, Descent through lower mesosophere ~20 min (60-40 km), complete descent without chute, Land in the ocean, no retrieval.
Science/Instruments	Extra Low Freq, Radiometer, Temperature, Pressure + Chute deployment video camera + GPS & science data downlink
Potential Inst-S/C Commonality	n/a
Desired Launch Vehicle	Terrier-Orion
Launch Date	Any
Mission Duration	~20 min science with real-time data downlink, passive descent
Mission Class	D/E
Technology Cutoff	existing technologies except for MegaChute
Minimum TRL at End of Phase B	6
	Spacecraft
Redundancy	Single-string
Stabilization & Control	No active control
Heritage	Sounding rockets and balloon missions for all but Mega-Chute
L/V Capability, kg	about 500 kg
Radiation Total Dose	n/a –some minor SEU risk
GPS	Yes
P/L Mass CBE, kg	6.2
P/L Power CBE, W	4.2
P/L Data Rate CBE, kb/s	60000
P/L Pointing, arcsec	3600
Tracking Network	0
Contingency Carried By	Subsystems

Table 8 – System Worksheet for the Mega-Chute, Case 1

Dryden MegaChute - Case 1 - Minimum Science Mission

Legend	
(blue)	Inputs from Subsystems
(red)	Inputs from Systems
(yellow)	Inputs from other systems
(green)	Calculated

SYSTEMS WORKSHEET

Analyst: Elisabeth Lamassoure
Start Date: 7/12/2005

Stabilization - cruise	3-Axis		Pointing Direction - cruise	n/a				
Stabilization - science	3-Axis		Pointing Direction - science	in-situ		Mission Duration	3.6	hr
						Max probe sun distance	1	AU
Pointing Control	3600	arcsec	Radiation Total Dose, krad	n/a		Instrument Data Rate	60,000	kb/s
Pointing Knowledge	1800	arcsec	Science BER	n/a		Data Storage	0	Gb
Pointing Stability	N/A	arcsec/sec	Redundancy	SS		Total Mission Data Volume	0	Mbits
Determined by:	TBD					Maximum Link Distance	200	km
			Technology Cutoff	2005		Return Data Rate	60,000	kb/s

Send / Request	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Recovery (n/a here)	Mode 2 Power (W) Final descent	Mode 3 Power (W) MegaChute Release	Mode 4 Power (W) Mesosphere Science	Mode 5 Power (W) MegaChute Deploy	Mode 6 Power (W) Launch
Power Mode Duration (hours)					0	3	0.00	0.5	0.02	0.08
Science Payload										
Instruments	21.2%	6.2	30%	8.1	0.0	0.0	0.0	4.2	0.0	0.0
Science Payload Total	21.2%	6.2	30%	8.1	0.0	0.0	0.0	4.2	0.0	0.0
Gondola Bus										
Attitude Determination (no guidance)	3.5%	1.0	11%	1.1	0.0	13.0	21.0	21.0	21.0	21.0
Command & Data (allocation)	1.7%	0.5	30%	0.7	0.0	0.0	5.0	5.0	5.0	5.0
Power	9.0%	2.6	30%	3.4	1.3	2.1	2.7	4.2	4.0	1.4
Structures & Mechanisms	14.3%	4.2	30%	5.5	0.0	0.0	0.0	0.0	0.0	0.0
S/C Adapter	4.6%	1.3	30%	1.7						
Cabling	6.1%	1.8	30%	2.3						
Telecomm	5.9%	1.7	0%	1.7	20.0	20.0	20.0	40.0	40.0	0.0
Thermal	1.1%	0.3	24%	0.4	0.0	0.0	0.0	0.0	0.0	0.0
Gondola Bus Total		23.1	24%	28.6	21.3	35.1	48.7	70.2	70.0	27.4
Gondola Total (Dry)		29.3	25%	36.6	21.3	35.1	48.7	74.4	70.0	27.4
Subsystem Heritage Contingency		7.3	25%	25%						
System Contingency		1.5	5%	5%	6.4	10.5	14.6	22.3	21.0	8.2
Total Gondola + Payload with Contingency		38.1	of total	w/o addl pld	27.7	45.7	63.3	96.8	91.0	35.6
Final Descent System										
Final Descent System Total		0.0	30%	0.0	*0%*	***of total final descent floated***				
Total Floating Mass in Final Descent		38.1								
MegaChute System ROUGH ESTIMATE										
Canopy & Suspension Lines		220	0%	220	*ALLOCATION*	Diameter		80	m	0.29
Pneumatic Ring		11	50%	17						10
Pneumatic Tube Stalk		50	50%	75						
Deploy / Inflate System		10	50%	15		Aerial Density		4.38.E-02	kg/m^2	(+/- 200%)
Other			50%	0						
MegaChute System Total		291	12%	327	*113%*	***of total science floated***				
Total Floating Mass in Science Mode		290	does not include stalk							
Vehicle Total (Wet)		365	includes stalk							
L/V Adapter		0								
Launch Mass		365								
Launch Vehicle Capability		413	Terrier-Orion			**Launch Apogee Altitude**		75	km	60
						Mission Unique LV Contingency		0%		
						Fairing height		2.2	m	0.33
Launch Vehicle Margin (Margin/Capability)		48	12%			Fairing dia.		0.44	m	
SpaceCraft Mass Margin (Margin/Launch Mass)		48	13%							

Contingencies	Mass	Power
Instruments	30%	30%
Final Descent Chute	30%	0%
Mega-Chute	50%	0%
Gondola Bus	30%	30%

Table 9 - System Mass Equipment List for the Mega-Chute, Case 1, page 1 of 2

Instruments

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
ELF/VLF	1	5.00	5.00	30%	6.50			TBD			None
Temperature	1	0.10	0.10	30%	0.13			TBD			None
Pressure	1	0.10	0.10	30%	0.13			TBD			None
Radiometer	1	1.00	1.00	30%	1.30			TBD			None

Attitude Determination and Control System

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Sun Sensors	4	0.01	0.02	10%	0.02	0.0	0.0	Coarse Analog		6	TBD component with TBD performance
Video Cameras	4	0.05	0.20	10%	0.22	2.0	2.0	Video Cameras		6	TBD component with TBD performance
GPS Receivers	1	0.05	0.05	30%	0.07	1.0	1.0	Non-Space Qualified Micro-GPS		6	TBD component with TBD performance
IMU	1	0.75	0.75	10%	0.83	12.0	12.0	Litton, LN200S	DS-1, Clementine	9	0.1 deg/hr gyro bias stability, 50 micro-g accel bias; 3 gyros, 3

Power

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Li-SOCl2 Battery	1	1.13	1.13	30%	1.46			TBD		9	None
Load Switching* Boards	1	0.50	0.50	30%	0.65			TBD		9	None
Battery Control* Boards	1	0.50	0.50	30%	0.65			TBD		9	None
Diodes Boards	1	0.50	0.50	30%	0.65			TBD		9	None

Structures

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Primary Structure	1	3.10	3.10	30%	4.03			TBD		6	None
Secondary Structure	1	0.37	0.37	30%	0.48			TBD		6	None
Instrument Mounts	1	0.51	0.51	30%	0.66			TBD		6	None
Integration Hardware	1	0.22	0.22	30%	0.28			TBD		6	None
Adapter, Spacecraft side	1	1.33	1.33	30%	1.73			TBD		6	None
Cabling Harness	1	1.79	1.79	30%	2.33			TBD		7	None

Table 9 - System Mass Equipment List for the Mega-Chute, Case 1, page 2 of 2

Telecomm

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
UHF linear antenna	1	0.10	0.10	0%	0.10			TBD		0	None
S-Band omni antenna (FAA)	1	0.26	0.26	0%	0.26			TBD		0	None
UHF Transmitter	1	0.50	0.50	0%	0.50			TBD		0	None
FAA Transponder	1	0.75	0.75	0%	0.75			TBD		0	None
Coax Cable, flex (120)	2	0.07	0.14	0%	0.14			TBD		0	None

Thermal

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Thermal Surfaces	1	0.11	0.11	30%	0.14			TBD		7	None
Thermal Conduction Control	1	0.11	0.11	30%	0.14			TBD		6	None
Temperature Sensors	10	0.01	0.10	10%	0.11			TBD		7	None

3.2.3. Case 2: addition of mega-chute guidance

There are two main design changes from Case 1 to Case 2: the addition of guidance and mid-air recovery, and an increase to a 100-km launch altitude, for a descent through the whole mesosphere. While these systems would require a new parachute design, significant feed-forward will be in place from Case 1 in the areas of: parachute materials, manufacturing, qualification and testing for large sizes, gondola design, payload integration and launch, parachute deployment and stability.

The guidance system needs to be placed on the mega-chute, otherwise the drift on the mega-chute would be too large to compensate with a small parafoil descent system. Megachute guidance is considered sufficiently accurate for mid-air recovery if the following sequence is followed:

- The megachute system uses the existing ACS sensors for positioning and attitude determination, an extension of existing parafoil design algorithms for guidance control, and the existing suspension lines with the addition of two motors for control actuation.
- The mega-chute is released at 30 to 40 km altitude, and the vehicle free-falls on a small ribbon drogue chute down to about 10 km (g = 35 psf). This free-fall minimizes the accumulation of targeting errors during this part of the descent.
- At that altitude, a final descent parafoil is deployed very fast, to allow interception with a helicopter at about 3 km altitude.

The increase in altitude requires increasing the mega-chute diameter, at given payload mass, to achieve subsonic speeds. It is also possible that the mega-chute design would change for this case, based on: (1) potential problems encountered by the lower-altitude design with deployment and stability and (2) potential addition of features to improve steer-ability, such as flaps in the chute.

Gondola Design

The gondola design for Case 2 is very similar to Case 1.

- Even though the gondola can be recovered, along with all its recorded science data, the Case 2 design includes the same capability for real-time data downlink as Case 1. This provides a back-up in case the guidance and recovery phases don't succeed as planned.

- The guidance and mid-air recovery capabilities rely heavily on a new mega-chute design, and the addition of a final descent system. The main change on the gondola is simply the inclusion of increased processing capability, and guidance software based on parafoil guidance algorithms heritage. The mass and power of the CDS was conservatively doubled to account for this additional capability.
- The steering system for the megachute is envisioned to use two motors. Such a system is likely to need thermal control, in order to remain sufficiently warm in the rarefied flow of the mesosphere, where the shaded part of the vehicle will be loosing heat. The Case 2 Thermal subsystem includes an allowance for the mass and power requirements of thermostats and heaters for this purpose.
- The additional CDS and thermal power can be handled with the same Power subsystem design as in Case 1, without any increase in the battery size.

These changes result in a total increase of a few kg on the gondola system, which now weighs 31 kg CBE and 41 kg with 30% contingency.

Vehicle Mass Budget

These changes result in a total increase of a few kg on the gondola system, which now weighs 31 kg CBE and 41 kg with 30% contingency.

The main mass changes for Case 2 are in the parachutes systems. A re-design of the parachutes system will likely be needed for this case, due to the additional requirement of accurate guidance. Here however, the parachutes systems mass estimates for Case 2 were simply scaled from Case 1 based on simple rules, as a means to develop a first-cut comparison between these cases.

- A final descent system is added to allow mid-air recovery after delivery to the right descent corridor by the mega-chute guidance system. The mass of this system was estimated parametrically based on experience with similar systems:
    - The parafoil mass is estimated at about 2% of the payload (gondola) mass. This parachute would be deployed by separation of the ribbon drogue chute.
    - The mass of the drogue parachute is estimated at about 4% of the payload (gondola) mass. This chute would be deployed by the separation of the mega-chute.
    - This results is a total mass of about 2.5 kg, to which 30% mass contingency was added given prior experience with such systems.
- The payload for the mega-chute now includes both the gondola and the final descent system, with a total mass + contingency of about 45 kg. This mass increase, together with the higher deployment altitude, lead to an increase in the mega-chute size, to a diameter of 130 m (or equivalent if the shape is not round). The mass of the canopy and suspension lines was scaled from Case 1, proportionally to the total area of the parachute.
- The mass of the pneumatic ring, whose sizes increases with the mega-chute size, was scaled in the same way. The mass of the pneumatic tub stalk mass and deployment systems were kept constants.

This leads to a total floated mass of about 690 kg, and a total launch mass of 760 kg. This is a 100% increase in launch mass for a <20% increase in mega-chute payload mass. The volume of the stowed mega-chute alone is close to 1 m^3.

Mass & Power Summary Sheets

The system sheets for Case 2 are shown on the following pages. These sheets include study guidelines and assumptions, the system worksheets and the equipment lists for the MegaChute vehicle.

Table 10 – System Guidelines for the Mega-Chute, Case 2

Team X Study Guidelines

Dryden MegaChute - Case 2 - Guided Science Mission

	Programmatics/Mission
Customer	**Kurt Kloesel**
Study Lead	**Bob Oberto / Bob Kinsey**
Mission	**MegaChute (Dryden)**
Target Body	**Earth mesosphere**
Trajectory	**Launch by sounding rocket to ~75 km, Descent through lower mesosophere ~20 min (60-40 km), complete descent with guidance, Mid-air retrieval**
Science/Instruments	**Extra Low Freq, Radiometer, Temperature, Pressure + Chute deployment video camera + GPS & science data downlink**
Potential Inst-S/C Commonality	**n/a**
Desired Launch Vehicle	**Terrier-Black Brant Mod 2**
Launch Date	**Any**
Mission Duration	**~20 min science with real-time data downlink + Guidance, Fast free-fall followed by parafoil descent TBD**
Mission Class	**D/E**
Technology Cutoff	**existing technologies except for MegaChute**
Minimum TRL at End of Phase B	**6**
	Spacecraft
Redundancy	**Single-string**
Stabilization & Control	**GPS & gyro + algorithms + 2 motors used to control the Mega-Chute trajectory**
Heritage	**Sounding rockets and balloon missions for all but Mega-Chute**
L/V Capability, kg	**more than about 1200 kg expected - capability in work**
Radiation Total Dose	**n/a —some minor SEU risk**
GPS	**Yes**
P/L Mass CBE, kg	**6.2**
P/L Power CBE, W	**4.2**
P/L Data Rate CBE, kb/s	**60000**
P/L Pointing, arcsec	**3600**
Tracking Network	**0**
Contingency Carried By	**Subsystems**

Table 11 – System Worksheet for the Mega-Chute, Case 2

Dryden MegaChute - Case 2 - Guided Science Mission

SYSTEMS WORKSHEET

Analyst: Elisabeth Lamassoure
Start Date: 7/12/2005

Legend	
(blue)	Inputs from Subsystems
(red)	Inputs from Systems
(yellow)	Inputs from other systems
(green)	Calculated

Stabilization - cruise	3-Axis		Pointing Direction - cruise	n/a			
Stabilization - science	3-Axis		Pointing Direction - science	in-situ	Mission Duration	3.6	hr
					Max probe sun distance	1	AU
Pointing Control	3600	arcsec	Radiation Total Dose, krad	n/a	Instrument Data Rate	60,000	kb/s
Pointing Knowledge	1800	arcsec	Science BER	n/a	Data Storage	0	Gb
Pointing Stability	N/A	arcsec/sec	Redundancy	SS	Total Mission Data Volume	0	Mbits
Determined by:	TBD				Maximum Link Distance	200	km
			Technology Cutoff	2005	Return Data Rate	60,000	kb/s

Send / Request	Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Recovery	Mode 2 Power (W) Final descent	Mode 3 Power (W) MegaChute Release	Mode 4 Power (W) Mesosphere Science	Mode 5 Power (W) MegaChute Deploy	Mode 6 Power (W) Launch	
Power Mode Duration (hours)					0	3	0.00	0.5	0.02	0.08	
Science Payload											
Instruments	*19.9%*	6.2	30%	8.1	0.0	0.0	0.0	4.2	0.0	0.0	
Science Payload Total	*19.9%*	**6.2**	**30%**	**8.1**	0.0	0.0	0.0	4.2	0.0	0.0	
Gondola Bus											
Attitude Control	*3.3%*	1.0	11%	1.1	0.0	13.0	21.0	21.0	21.0	21.0	
Command & Data (allocation)	*3.2%*	1.0	50%	1.5	0.0	0.0	10.0	10.0	10.0	10.0	
Power	*8.4%*	2.6	30%	3.4	1.3	2.1	2.7	4.2	4.0	1.4	
Structures & Mechanisms	*13.9%*	4.3	30%	5.6	0.0	0.0	0.0	0.0	0.0	0.0	
S/C Adapter	*4.7%*	1.5	30%	1.9							
Cabling	*5.9%*	1.8	30%	2.4							
Telecomm	*5.6%*	1.7	0%	1.7	20.0	20.0	20.0	40.0	40.0	0.0	
Thermal	*3.9%*	1.2	28%	1.6	1.9	1.9	1.9	1.9	1.9	1.9	
Gondola Bus Total		**25.0**	**25%**	**31.2**	23.2	37.1	55.6	77.2	76.9	34.3	
Gondola Total (Dry)		**31.2**	**26%**	**39.3**	23.2	37.1	55.6	81.4	76.9	34.3	
Subsystem Heritage Contingency		8.1	*26%*	*26%*							
System Contingency		1.3	*4%*	*4%*	7.0	11.1	16.7	24.4	23.1	10.3	
Total Gondola + Payload with Contingency		**40.5**	*of total*	*w/o addl pld*	**30.2**	**48.2**	**72.3**	**105.8**	**100.0**	**44.6**	**203 W-hr**
Final Descent System											
Final Descent System Total		**2.4**	**30%**	**3.6**	*8%*	***of total final descent floated***					
Total Floating Mass in Final Descent		**44.2**									

	Mass (kg)	Cont. %	CBE+ Cont. (kg)						
MegaChute System ROUGH ESTIMATE						for subsonic @ 90km			
Canopy & Suspension Lines	581	0%	581	***ALLOCATION***	Diameter	130	m	0.77	m^3
Pneumatic Ring	29	50%	44					27	ft^3
Pneumatic Tube Stalk	50	50%	75						
Deploy / Inflate System	10	50%	15		Aerial Density	4.E-02	kg/m^2	(+/- 200%)	
Steering System (2 motors)	2	50%	3						
MegaChute System Total	**672**	**7%**	**718**	*104%*	***of total science floated***				
Total Floating Mass in Science Mode	**687**	does not include stalk							
Vehicle Total (Wet)	**762**	includes stalk							
L/V Adapter	0								
Launch Mass	**762**								
Launch Vehicle Capability	**963**	Terrier-Black Brant Mod 2			**Launch Apogee Altitude**	**100**	**km**	**90**	**km science**
					Mission Unique LV Contingency				
					Fairing height	1.3	m	0.31	m^3
Launch Vehicle Margin (Margin/Capability)	**202**	21%			Fairing dia.	0.6	m		
SpaceCraft Mass Margin (Margin/Launch Mass)	**202**	26%							

Contingencies	Mass	Power
Instruments	30%	30%
Final Descent Chute	30%	0%
Mega-Chute	50%	0%
Gondola Bus	30%	30%

Table 12 - System Mass Equipment List for the Mega-Chute, Case 2, page 1 of 2

Instruments

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
ELF/VLF	1	5.00	5.00	30%	6.50			TBD			None
Temperature	1	0.10	0.10	30%	0.13			TBD			None
Pressure	1	0.10	0.10	30%	0.13			TBD			None
Radiometer	1	1.00	1.00	30%	1.30			TBD			None

Attitude Determination and Control System

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Sun Sensors	4	0.01	0.02	10%	0.02	0.0	0.0	Coarse Analog		6	TBD component with TBD performance
Video Cameras	4	0.05	0.20	10%	0.22	2.0	2.0	Video Cameras		6	TBD component with TBD performance
GPS Receivers	1	0.05	0.05	30%	0.07	1.0	1.0	Non-Space Qualified Micro-GPS		6	TBD component with TBD performance
IMU	1	0.75	0.75	10%	0.83	12.0	12.0	Litton, LN200S	DS-1, Clementine	9	0.1 deg/hr gyro bias stability, 50 micro-g accel bias; 3 gyros, 3

Power

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Li-SOCl2 Battery	1	1.13	1.13	30%	1.46			TBD		9	None
Load Switching* Boards	1	0.50	0.50	30%	0.65			TBD		9	None
Battery Control* Boards	1	0.50	0.50	30%	0.65			TBD		9	None
Diodes Boards	1	0.50	0.50	30%	0.65			TBD		9	None

Structures

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Primary Structure	1	3.22	3.22	30%	4.19			TBD		6	None
Secondary Structure	1	0.39	0.39	30%	0.50			TBD		6	None
Instrument Mounts	1	0.51	0.51	30%	0.66			TBD		6	None
Integration Hardware	1	0.23	0.23	30%	0.29			TBD		6	None
Adapter, Spacecraft side	1	1.45	1.45	30%	1.89			TBD		6	None
Cabling Harness	1	1.84	1.84	30%	2.39			TBD		7	None

Table 12 - System Mass Equipment List for the Mega-Chute, Case 2, page 2 of 2

Telecomm											
Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
UHF linear antenna	1	0.10	0.10	0%	0.10			TBD		0	None
S-Band omni antenna (FAA)	1	0.26	0.26	0%	0.26			TBD		0	None
UHF Transmitter	1	0.50	0.50	0%	0.50			TBD		0	None
FAA Transponder	1	0.75	0.75	0%	0.75			TBD		0	None
Coax Cable, flex (120)	2	0.07	0.14	0%	0.14			TBD		0	None

Thermal											
Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Thermal Surfaces	1	0.34	0.34	30%	0.44			TBD		7	None
Thermal Conduction Control	1	0.04	0.04	30%	0.05			TBD		6	None
Thermostats (Number)	5	0.05	0.25	30%	0.33			TBD		7	None
Heaters (Number)	10	0.05	0.50	30%	0.65			TBD		7	None
Temperature Sensors	10	0.01	0.10	10%	0.11			TBD		7	None

3.2.4. Case 3: full science application

Case 3 achieves the same altitude and guidance performance as Case 2, but now includes a full science instrument package, capable of meeting the “Phase D” science requirements. This package has a total mass of 30 kg and a total power requirement of almost 90 W, which represents a 5-fold increase in mass, and a 20-fold increase in power, over Cases 1 and 2. . While this mass increase might require a new parachute design, significant feed-forward will be in place from Cases 1 and 2 in the areas of : parachute materials, manufacturing, qualification and testing for large sizes, gondola design, payload integration and launch, parachute deployment and stability through the whole mesosphere, parachute guidance, and mid-air recovery.

Gondola design changes

- As the cost and science value of megachute missions increases, so does the importance of back-up data. For this reason, Case 3 also includes the capability for real-time data downlink in addition to the recovery capability.
- The same Telecom subsystem is able to handle the increase instrument data rate. The drivers for instrument data rate are indeed the 4 video cameras responsible for capturing mega-chute deployment.
- In order to support the megachute steering function, the Case 3 gondola design includes the same CDS and Thermal changes as for Case 2.
- The size of the primary battery for Case 3 is now greater, so as to provide energy to the larger instrument suite.
- The increase in the complexity and mass of the gondola structure is the main impact of the increased payload on the gondola design.

These changes result in a total increase 130% on the gondola system mass, which now weighs 72 kg CBE and 93 kg with 30% contingency.

Vehicle Mass Summary

A re-design of the parachutes system will likely be needed for this case, due to the significant change in payload mass. Here however, the parachutes systems mass estimates for Case 3 were simply scaled with the increase in gondola mass from Case 2, as a means to develop a first-cut comparison between these cases.

- The parafoil and drogue chute scale with gondola mass, bringing the total final descent mass to 100 kg.
- To support the mega-chute diameter for Case 3 needs to increase to almost 200 m in order to support this payload mass. This translates into large mass increases for the canopy, suspension lines, and pneumatic ring.

The resulting system has a total floated mass of about 1550 kg with contingency, and a total launch mass of more than 1600 kg. The volume of the stowed mega-chute alone is close to 2 m^3.

Mass & Power Summary Sheets

The system sheets for Case 3 are shown on the following pages. These sheets include study guidelines and assumptions, the system worksheets and the equipment lists for the MegaChute vehicle.

Table 13 – System Guidelines for the Mega-Chute, Case 3

Team X Study Guidelines	
Dryden MegaChute - Case 3 - Guided Mission, Best Science	
	Programmatics/Mission
Customer	Kurt Kloesel
Study Lead	Bob Oberto / Bob Kinsey
Mission	MegaChute (Dryden)
Target Body	Earth mesosphere
Trajectory	Launch by sounding rocket to ~110 km, Descent through lower mesosophere ~30 min (90-50 km), complete descent with guidance, Mid-air retrieval
Science/Instruments	Radar, LIDAR, UV-IR, Laser Spectrometer, High-speed camera, Magnetometer, TOD Mass spectrometer, Temperature, Pressure + Chute deployment video camera + GPS & science data downlink
Potential Inst-S/C Commonality	n/a
Desired Launch Vehicle	Terrier-Black Brant Mod 2
Launch Date	Any
Mission Duration	~30 min science with real-time data downlink + Guidance, Fast free-fall followed by parafoil descent TBD
Mission Class	D/E
Technology Cutoff	existing technologies except for MegaChute
Minimum TRL at End of Phase B	6
	Spacecraft
Redundancy	Single-string
Stabilization & Control	No active control
Heritage	Sounding rockets and balloon missions for all but Mega-Chute
L/V Capability, kg	about 500 kg
Radiation Total Dose	n/a –some minor SEU risk
GPS	Yes
P/L Mass CBE, kg	29.7
P/L Power CBE, W	88.2
P/L Data Rate CBE, kb/s	60000
P/L Pointing, arcsec	3600
Tracking Network	0
Contingency Carried By	Subsystems

Table 14 – System Worksheet for the Mega-Chute, Case 3

Dryden MegaChute - Case 3 - Guided Mission, Best Science

SYSTEMS WORKSHEET

Analyst: Elisabeth Lamassoure
Start Date: 7/12/2005

Legend	
(blue)	Inputs from Subsystems
(red)	Inputs from Systems
(yellow)	Inputs from other systems
(green)	Calculated

Stabilization - cruise	3-Axis	
Stabilization - science	3-Axis	
Pointing Control	3600	arcsec
Pointing Knowledge	1800	arcsec
Pointing Stability	N/A	arcsec/sec
Determined by:	TBD	

Pointing Direction - cruise	n/a
Pointing Direction - science	in-situ
Radiation Total Dose, krad	n/a
Science BER	n/a
Redundancy	SS
Technology Cutoff	2005

Mission Duration	3.6	hr
Max probe sun distance	1	AU
Instrument Data Rate	60,000	kb/s
Data Storage	0	Gb
Total Mission Data Volume	0	Mbits
Maximum Link Distance	200	km
Return Data Rate	60,000	kb/s

Send / Request	Mass Fraction	COMPARISON CASE 1	COMPARISON CASE 2	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Recovery (n/a here)	Mode 2 Power (W) Final descent	Mode 3 Power (W) MegaChute Release	Mode 4 Power (W) Mesosphere Science	Mode 5 Power (W) MegaChute Deploy	Mode 6 Power (W) Launch	
Power Mode Duration (hours)							0	3	0.00	0.5	0.02	0.08	
Science Payload													
Instruments	*41.4%*	*6.2*	*6.2*	29.7	30%	38.6	0.0	0.0	0.0	88.2	0.0	0.0	
Science Payload Total	*41.4%*	*6.2*	*6.2*	**29.7**	**30%**	**38.6**	0.0	0.0	0.0	88.2	0.0	0.0	
Gondola Bus													
Attitude Control	*1.4%*	*1.0*	*1.0*	1.0	11%	1.1	0.0	13.0	21.0	21.0	21.0	21.0	
Command & Data (allocation)	*1.4%*	*0.5*	*1.0*	1.0	50%	1.5	0.0	0.0	10.0	10.0	10.0	10.0	
Power	*4.0%*	*2.6*	*2.6*	2.9	30%	3.7	1.3	2.1	2.7	9.7	4.0	1.4	
Structures & Mechanisms	*15.0%*	*4.2*	*4.3*	10.8	30%	14.0	0.0	0.0	0.0	0.0	0.0	0.0	
S/C Adapter	*2.9%*	*1.3*	*1.5*	2.1	30%	2.7							
Cabling	*6.5%*	*1.8*	*1.8*	4.7	30%	6.1							
Telecomm	*2.4%*	*1.7*	*1.7*	1.7	0%	1.7	20.0	20.0	20.0	40.0	40.0	0.0	
Thermal	*2.1%*	*0.3*	*1.2*	1.5	29%	1.9	4.6	4.6	4.6	4.6	4.6	4.6	
Gondola Bus Total		*23.1*	*25.0*	**42.0**	**27%**	**53.4**	25.9	39.8	58.3	85.3	79.6	37.0	
Gondola Total (Dry)		*28.3*	*31.2*	**71.7**	**28%**	**92.0**	25.9	39.8	58.3	173.5	79.6	37.0	
Subsystem Heritage Contingency		*7.3*	*8.1*	20.3	*28%*	*28%*							
System Contingency		*1.5*	*1.3*	1.3	*2%*	*2%*	7.8	11.9	17.5	52.1	23.9	11.1	
Total Gondola + Payload with Contingency		*38.1*	*40.5*	**93.2**	*of total*	*w/o addl pld*	**33.7**	**51.7**	**75.8**	**225.6**	**103.5**	**48.1**	**274 W-hr**
Final Descent System													
Final Descent System Total		*0*	*2*	**5.6**	**30%**	**7.3**	*7%*	***of total final descent floated***					
		0	*0*										
Total Floating Mass in Final Descent		*38.1*	*44.2*	**100.5**									
MegaChute System ROUGH ESTIMATE													
Canopy & Suspension Lines		*220*	*581*	1322	0%	1322			Diameter	196	m	1.75	m^3
Pneumatic Ring		*11*	*29*	66	50%	99						62	ft^3
Pneumatic Tube Stalk		*50*	*50*	50	50%	75							
Deploy / Inflate System		*10*	*10*	10	50%	15	*(2 kg of gas)*		Aerial Density	4.E-02	kg/m^2	(+/- 200%)	
Steering System		*0*	*2*	2	50%	3							
MegaChute System Total		*291*	*672*	**1450**	**4%**	**1514**	*98%*	***of total science floated***					
Total Floating Mass in Science Mode		*290*	*687*	**1539**	does not include stalk								
Vehicle Total (Wet)		*365*	*762*	**1614**	includes stalk								
L/V Adapter				0									
Launch Mass		*365*	*762*	**1614**									
Launch Vehicle Capability				**963**	Terrier-Black Brant Mod 2				**Launch Apogee Altitude**	**100**	**km**		
									Mission Unique LV Contingency				
									Fairing height	3.0	m	0.71	m^3
Launch Vehicle Margin (Margin/Capability)				**-651**	-68%				Fairing dia.	0.6	m		
SpaceCraft Mass Margin (Margin/Launch Mass)				**-651**	-40%								

Contingencies	Mass	Power
Instruments	30%	30%
Final Descent Chute	30%	0%
Mega-Chute	50%	0%
Gondola Bus	30%	30%

Table 15 - System Mass Equipment List for the Mega-Chute, Case 3, page 1 of 2

Instruments

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Radar	1	5.00	5.00	30%	6.50			TBD			None
Temperature	1	0.10	0.10	30%	0.13			TBD			None
Pressure	1	0.10	0.10	30%	0.13			TBD			None
LIDAR	1	8.00	8.00	30%	10.40			TBD			None
High-Speed Camera	1	3.00	3.00	30%	3.90			TBD			None
UV/IR	1	7.00	7.00	30%	9.10			TBD			None
Laser Spectrometer	1	2.00	2.00	30%	2.60			TBD			None
Magnetometer	1	0.50	0.50	30%	0.65			TBD			None
TOF mass spec	1	4.00	4.00	30%	5.20			TBD			None

Attitude Determination and Control System

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Sun Sensors	4	0.01	0.02	10%	0.02	0.0	0.0	Coarse Analog		6	TBD component with TBD performance
Video Cameras	4	0.05	0.20	10%	0.22	2.0	2.0	Video Cameras		6	TBD component with TBD performance
GPS Receivers	1	0.05	0.05	30%	0.07	1.0	1.0	Non-Space Qualified Micro-GPS		6	TBD component with TBD performance
IMU	1	0.75	0.75	10%	0.83	12.0	12.0	Litton, LN200S	DS-1, Clementine	9	0.1 deg/hr gyro bias stability, 50 micro-g accel bias; 3 gyros, 3

Power

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Li-SOCl2 Battery	1	1.35	1.35	30%	1.76			TBD		9	None
Load Switching* Boards	1	0.50	0.50	30%	0.65			TBD		9	None
Battery Control* Boards	1	0.50	0.50	30%	0.65			TBD		9	None
Diodes Boards	1	0.50	0.50	30%	0.65			TBD		9	None

Structures

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Primary Structure	1	7.04	7.04	30%	9.15			TBD		6	None
Secondary Structure	1	0.85	0.85	30%	1.10			TBD		6	None
Instrument Mounts	1	2.39	2.39	30%	3.10			TBD		6	None
Integration Hardware	1	0.49	0.49	30%	0.64			TBD		6	None
Adapter, Spacecraft side	1	2.07	2.07	30%	2.69			TBD		6	None
Cabling Harness	1	4.68	4.68	30%	6.08			TBD		7	None

Table 15 - System Mass Equipment List for the Mega-Chute, Case 3, page 2 of 2

Telecomm

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
UHF linear antenna	1	0.10	0.10	0%	0.10			TBD		0	None
S-Band omni antenna (FAA)	1	0.26	0.26	0%	0.26			TBD		0	None
UHF Transmitter	1	0.50	0.50	0%	0.50			TBD		0	None
FAA Transponder	1	0.75	0.75	0%	0.75			TBD		0	None
Coax Cable, flex (120)	2	0.07	0.14	0%	0.14			TBD		0	None

Thermal

Component	Flt Units	Mass/ Unit (kg)	Total Mass (kg)	Contingency %	CBE + Contingency (kg)	Peak Power per Unit (W)	Aver. Power per Unit (W)	Vendor	Heritage	TRL	Description/Comments
Thermal Surfaces	1	0.57	0.57	30%	0.74			TBD		7	None
Thermal Conduction Control	1	0.09	0.09	30%	0.12			TBD		6	None
Thermostats (Number)	5	0.05	0.25	30%	0.33			TBD		7	None
Heaters (Number)	10	0.05	0.50	30%	0.65			TBD		7	None
Temperature Sensors	10	0.01	0.10	10%	0.11			TBD		7	None

3.3. Launch Vehicle

The *Sounding Rocket Program Handbook* published by NASA GSFC provides a complete guide to the user of NASA sounding rockets. This guide was used, in addition to discussion with sounding rocket experts, to estimate the capability of the launch vehicles for the mega-chute mission. The guide is available on-line at: http://www.wff.nasa.gov/code810/docs/SRHB.pdf . All material in this paragraph refers to that document.

The mega-chute missions would use the sounding rockets beyond their typical mass /altitude range: higher masses launched to lower altitudes. While it is believed that a custom design would be feasible, the launch vehicle capability numbers provided in this report are only first-order estimates.

- Further analysis is required to assess feasibility and confirm capability. Per sounding rocket experts, dynamic pressure on the inner stage is the limiting factor when trying to launch a greater mass to a lower altitude. Adding mass would lead to stability problems.
- **The key concern with these launch vehicle is the available volume in the payload fairing**. No more than about 1 m^3 is typically available in the payload fairings. This is already close to the volume required for the stowed mega-chute alone for Cases 1 and 2, not even considering the gondola system, pneumatic tubes and their inflation system, etc. This is clearly insufficient for Case 3.

3.3.1. Case 1: Terrier-Orion

- The recommended sounding rocket candidate for Case 1 is a Terrier-Improved Orion vehicle, a 2-stage spin-stabilized rocket system using a Terrier MK12 Mod 1 for the first stage and an Improved Orion motor for the second stage. The total mass of the vehicle without payload is 1316 kg.
- The vehicle supports two payload configurations: the bulbous 17.25-inch (44-cm) diameter would be chosen for the mega-chute to accommodate the sheer packing volume of the chute. This vehicle comes with a full cadre of support systems, including fixed or deployable nose cones; fine course, rate control, and magnetic ACS systems; separation and despin systems; and forward and aft recovery systems. Instead of a yo-yo, the cold gas RCS

system option is recommended to des-pin the mega-chute vehicle before release; this system can also tailor the release attitude in order to ensure proper deployment.

- The launch vehicle capability for sounding rockets depends not only on the apogee altitude, but also on the downrange the mission needs to achieve. Since down-range is not critical to a successful-megachute mission, only the capability curves for the shortest down-range were considered. By extending the performance curved reproduced below, the capability to 75 km altitude is estimated at slightly higher than 400 kg.
- This capability is approximately appropriate for the Case 1 mega-chute mission. However, volume might be limited. An analysis of the stowed megachute volume is required.

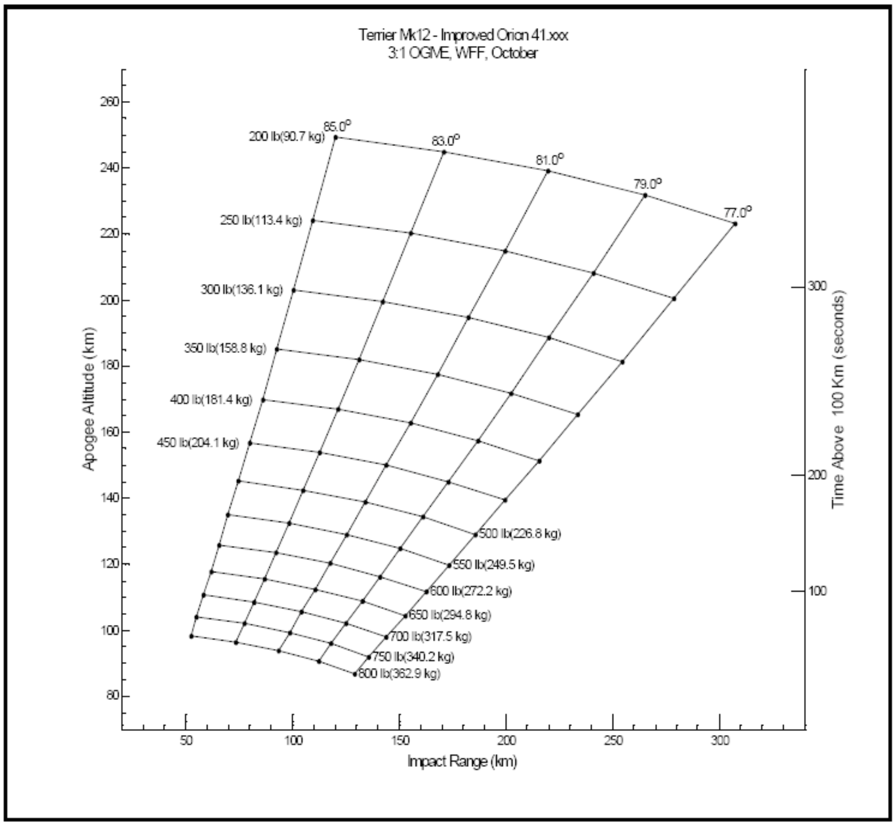


Figure 10 – Terrier MK12-ImprovedOrion Predicted Vehicle Performance

(Reference: Figure F.8-2, page 165 of NASA 810-HB-SRP, June 2005)

3.3.2. Case 2: Terrier-Black Brant IX (9)

- The best sounding rocket candidate for Case 2 is a Terrier-Black Brant 9 vehicle, which uses the Black Brant V rocket motor. The first stage consists of either a Terrier MK12 Mod 1 or a Terrier MK70 rocket.
- The standard payload configuration is a 17.26-inch (44-cm) diameter with a 3:1 ogive nose shape, corresponding to a length of about 1.2 m. This might not provide sufficient total payload volume.
- The launch vehicle capability for sounding rockets depends not only on the apogee altitude, but also on the downrange the mission needs to achieve. Since down-range is not critical to a successful-megachute mission, only the capability curves for the shortest down-range were considered. By extending the performance curved reproduced below with an exponential fit, the capability to 100 km altitude is estimated at 900 kg to 1000 kg.

- This capability is approximately appropriate for the Case 2 mega-chute mission, but not for the Case 3 mission. Another vehicle, or launch site/elevation/range combination might be possible for that case. This requires further investigation.

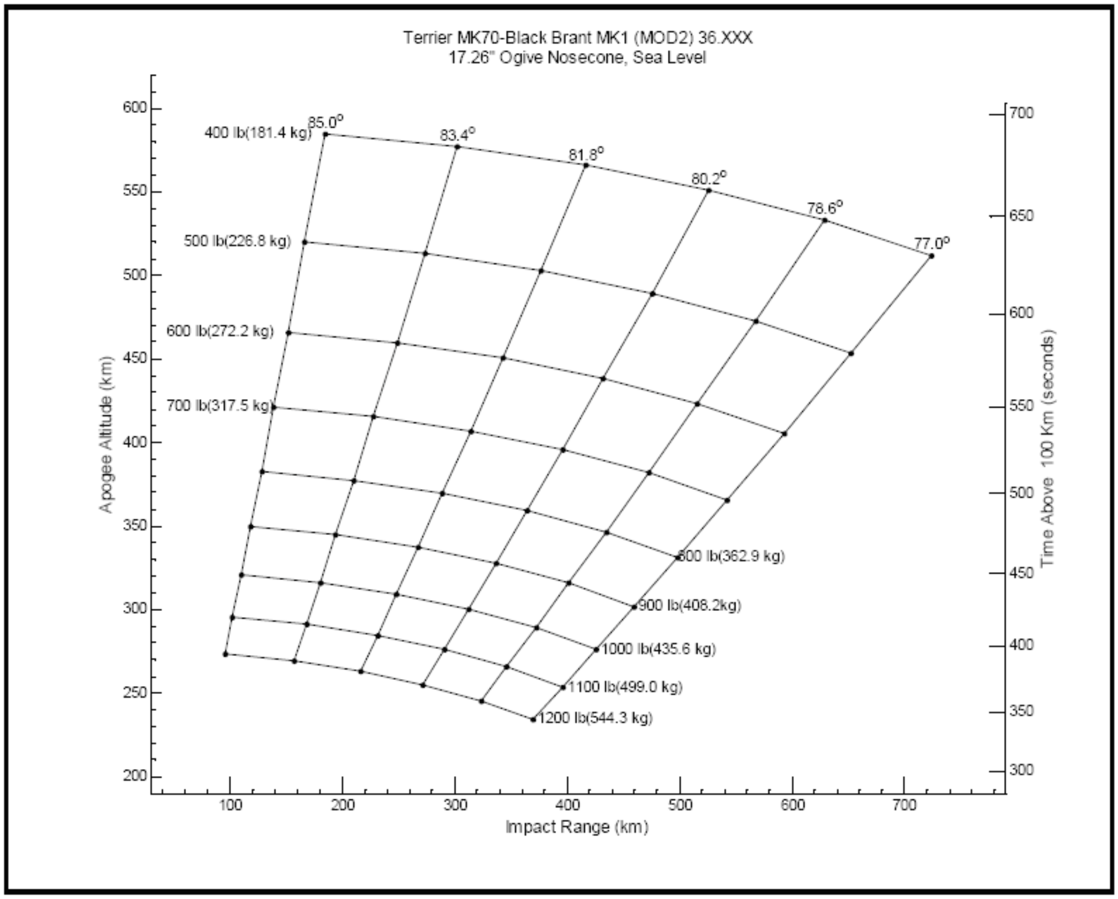


Figure 11 – Terrier MK70-Black Brant MK1(Mod 2) Predicted Vehicle Performance

(Reference: Figure F.5-6, page 157 of NASA 810-HB-SRP, June 2005)

3.3.3. Case 3: Talos-Taurus-Black Brant XI (11)

- The best sounding rocket candidate for Case 3 is the three stage Black Brant 11 vehicle. The Black Brant XI rocket system is a three stage system used primarily to carry heavy payloads, to high altitudes. The first and second stages are the Mk 11 Mod 5 Talos rocket motor and the Taurus motor. The third stage is a modified Black Brant VC motor. The standard payload configuration is a 17.26-inch (44-cm) diameter with a 3:1 ogive nose shape, corresponding to a length of about 1.2 m.
- The Case 3 System Worksheet uses a Terrier Black Brant 9. The worksheet indicates that the launch margin is negative. A discussion with the personnel at NASA-Wallops indicates that the three stage Black Brant 11 vehicle will provide the performance required. The volume of payload and the aerodynamic response of the payload still requires analysis. The additional cost of the three stage vehicle verses a two stage vehicle is minimal (~$100K) and is within the budget contingency.
- Case 3 also provides an rough order of magnitude for the estimation for Science Objective Phase C. The payload is somewhat heavier, but the altitude is lower. Therefore, Case 3 provides a lower bound estimate for Phase C.

4. Parachute Design Challenges

4.1. System Description – Initial Concept

A conceptual design of the so-called "Mega-Chute" is presented in Figure 12 on below. It is extremely large and lightweight. The inflatable "Deployment Ring" can be seen around the parachute perimeter. The canopy has a planform diameter of 360 feet (110 meters), and a projected area of 2.3 acres. The typical parachute has a projected planform area of 45% of its laid out material area. Although the Mega-Chute may be somewhat flatter than the standard hemisphere due to its deployment ring, it will also need extra material in the ring, so this assumption for the canopy mass was used in the analysis. (Reference: Kloesel, K.J., Morgan, R., Gilland, J., Scarborough, S., "Feasibility of Aerodynamic Flight in the Mesospheric, Thermospheric and Exospheric Regions", NASA-HQ Report, Revolutionary Systems Concepts in Aeronautics 2004-05)

By keeping the shroud lines approximately 1.4 times the canopy diameter, it permits the parachute to enter a stable "gliding" mode with a lift to drag ratio of approximately one (in continuum flow), increasing the effective lift/drag coefficient (weight coefficient) to a value of 3. At an altitude where the atmospheric pressure is too low for continuum flow, a "Newtonian Flow" calculation indicates a Cp for the plan area of 2. For the analysis of descent rate, an assumption of an average reaction coefficient of 2.5 was made. 20% was added to the actual payload mass to allow for structural containment and deployment of the parachute.

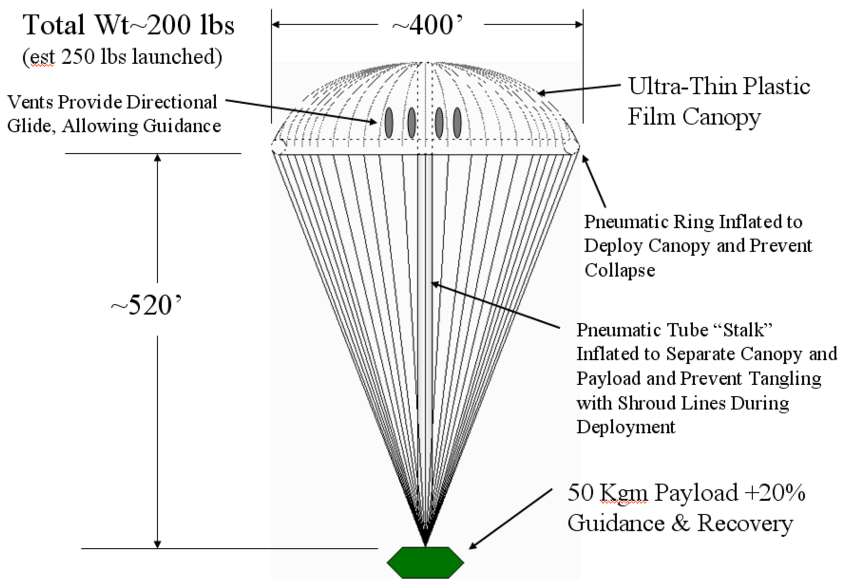


Figure 12 - Preliminary concept of the mega-meso chute
A parachute concept capable of extended duration sub-sonic flight in the mesosphere

4.1.1. Parachute Types – Non-Gliding

Although the initial concept considered a gliding parachute, the non-gliding parachute was re-examined. In considering stable, non-gliding parachute types, we wish to select a type that uses material efficiently to create drag, and can be designed with approximately 30% geometric porosity. One of the most efficient such types is the ringsail. Ringsail designs were used for both Beagle II and MER Mars landing parachutes.

However, constructing a parachute from film or reinforced film is somewhat different from using fabric and may lead to a different type of design. For example, the ringsail type has many panels with slots between. The panel edges carry much more stress than the rest of the fabric and stretch on the edges would change the shape of the slots and the performance of the canopy. Reinforcing the edges is probably necessary, but a ringsail has a lot of edge.

The photo shown in Figure 13a below is of a large ringsail parachute, with the open slots evident on close examination.

One alternative is a cruciform or a more advanced version called a tri-lobe, shown in Figure 13b below. In these types, the geometric porosity is created by a small number of vertical slots, rather than a large number of circumferential slots. This type of construction may be more mass-efficient for a parachute manufactured from film.

Figure 13 - Exemple Parachute Types : (a) Large ringsail (b) Cruciform

4.1.2. Gliding versus Ballistic

Gliding has several potential benefits that must be weighed against risk, these are:

- Increased drag coefficient
- Improved stability
- Trajectory control

The risks are that, with a parachute system operating so far outside of previous experience in terms of scale, mass ratio and Reynolds number, the system will not fly in a controlled, or controllable, manner. Un-damped pitch oscillations, coning and spiraling are examples of unwanted dynamics that are possible.

We are better able to design a system with high probability of success by aiming toward a very stable ballistic system. Stability can be achieved, independent of Reynolds number, by providing sufficient geometric porosity. A highly stable system may, in turn, be subject to less of the dynamics associated with high mass ratio.

It is our recommendation to base performance estimates, conservatively, on a ballistic system, but to continue to study gliding systems through FSI simulation in any follow-on phase. The payoffs are substantial for gliding, but it may pay to have a ballistic system as a fall-back.

4.1.3. Nomenclature

A few terms used in this report are not commonly used outside of parachute literature and may not be familiar to the reader.

Ballistic Coefficient $B = \frac{M}{C_D A}$ usually kg/m^2, but gm/m^2 is sometimes used in this report in order to more easily relate to material areal density in the same units. Ballistic coefficient is the scale-independent parameter that directly relates to descent velocity and time of flight.

Mass Ratio $R_M = \frac{M}{\rho A^{\frac{3}{2}}}$ A dimensionless parameter that governs the scaling of parachute inflation, dynamics and response to control input. Mega-Meso, even though very large, has a very high mass ratio – the payload mass is

greater than the apparent mass of the parachute. This would normally mean that the payload would be fully decelerated by the time the parachute is inflated to its full area. On the other hand, the actual mass of the parachute is high compared to the payload, leading to an unusual situation in terms of dynamic response.

Specific Strength The breaking strength of a material divided by it mass per unit length. By mixing mass and force units, leaving one Earth gravity implied, specific strength has units of length. For example, breaking strength in kgf, divided by lineal density in kg/m, gives specific strength in meters. This has the physical meaning of the maximum length of material that can hang in one Earth gravity without breaking under its own weight.

4.2. Materials

4.2.1. Areal Density and Strength

The feasibility of the Mega-Meso Parachute concept depends on the availability of extremely low areal-density materials. Candidate materials include films, fabrics and fiber-reinforced films. A summary of the specific strength of various films and fibers is included in an appendix to this report.

Fibers have a high specific strength compared to films, which means that the minimum weight membrane, for a given tensile strength, might advantageously be comprised of fibers or some combination of fibers and films. Some examples of available films, fibers and films reinforced by fibers are discussed below and their relative areal densities are compared in the chart following.

We assume a specific strength for Polyimid (Kapton or Upilex) film of 30,000 m. Published data is somewhat higher, but is based on 25.4 µm (0.001 inch) thickness. The thinner grades will generally not have as high specific strength. . The thickness represented in the chart are 7.6, 15.2 and 25.4 µm, all of which are available if a large minimum order and long lead time are acceptable. Note that the very thin grades are very easily torn and are generally difficult to fabricate. Based on some limited experience in our shop, we do not consider the 7.6 µm to be practical for use un-reinforced.

Tight weave fabric is calculated based on a converted specific strength of 100,000 m and an areal density scaled by the square-root of yarn density. This specific strength is a bit high for Kevlar, but should be realized with Vectran.

Weaving a more open fabric does not change the strength-density relationship, but does allow a lighter fabric for a given minimum denier yarn (e.g., 25 denier for Vectran). Given the high kinematic viscosity, an open weave may be usable without excessive permeability. If so, it appears that a fabric with areal density as low as 10 gm/m2 may be feasible. An analysis of the permeability of open-weave fabric at extremely low Reynolds numbers is included in the appendix.

The last approach studied is the use of a minimum gauge film with widely spaced reinforcing fibers. The film would be relieved of primary stress in the parachute membrane so that the thinnest gauge films can be used without tears propagating into total failure of the canopy.

Of available films found during this study, only Mylar was available in thinner gauges than 7.5 µm.

Table 16 – Material Characteristics

Name	t_min	t_min	s.g.	a. dens.
	µm	mil	gm/cc	gm/m^2
Mylar	4.2	0.17	1.39	5.8
Kapton	7.6	0.30	1.42	10.8
Upilex	7.5	0.30	1.47	11.0
Stratofilm	13.2	0.52	0.97	12.8
Tedlar	6.4	0.25	1.40	8.89

We were initially interested in Stratofilm, since so much development has gone into its fabrication and use for the Ultra-Long Duration Balloon (ULDB) program. We found that it is not available as thin as some other films nor does it have the strength of other films. However, given the similarity of the Mega-Meso environment, and the similarly low stress levels, any future design studies should include a detailed assessment of the ULDB experience.

Orcon Corporation makes fiber reinforced films for aircraft insulation. The picture below is of a 0.5 mil Mylar film with Polyester warp yarn and Kevlar fill yarn with approximately 0.25 inch spacing of the warp yarns. The areal density of this material is 24 gm/m^2. Their AN-36W reinforced film uses 0.25 mil Mylar film and weighs 17 gm/m^2.

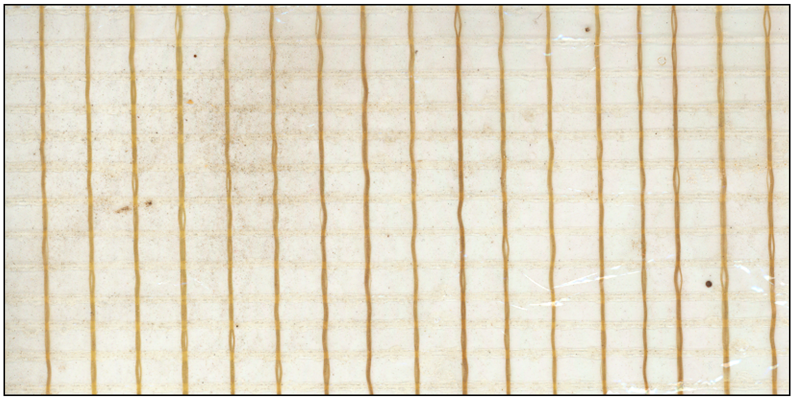


Figure 14 – Example Fiber Reinforced Film for Aircraft Insulation

In a conversation with an Orcon engineer, it was learned that 0.17 mil Mylar film is sometimes available, and that it is probably compatible with their process. For the purpose of mass estimation, they assume that the adhesive weighs 2.5 times the weight of the yarn, but is normally applied only to the fill yarns. On this basis, the estimated areal density of 100 denier Vectran, bonded to 0.17 mil Mylar in a 1 inch by 1 inch grid is 7.5 gm/m^2. Other combinations yarn weight and grid spacing are possible, but will not be significantly lighter.

The chart below summarizes the strength and areal density of the various materials studied. The strength of most of these materials is far greater than needed for the steady-state loads on the concept parachute, which are estimated to be less than 0.1 lb/in (1.8 kgf/m). However, at least for the fiber-reinforced films, this strength comes with only a small mass increase.

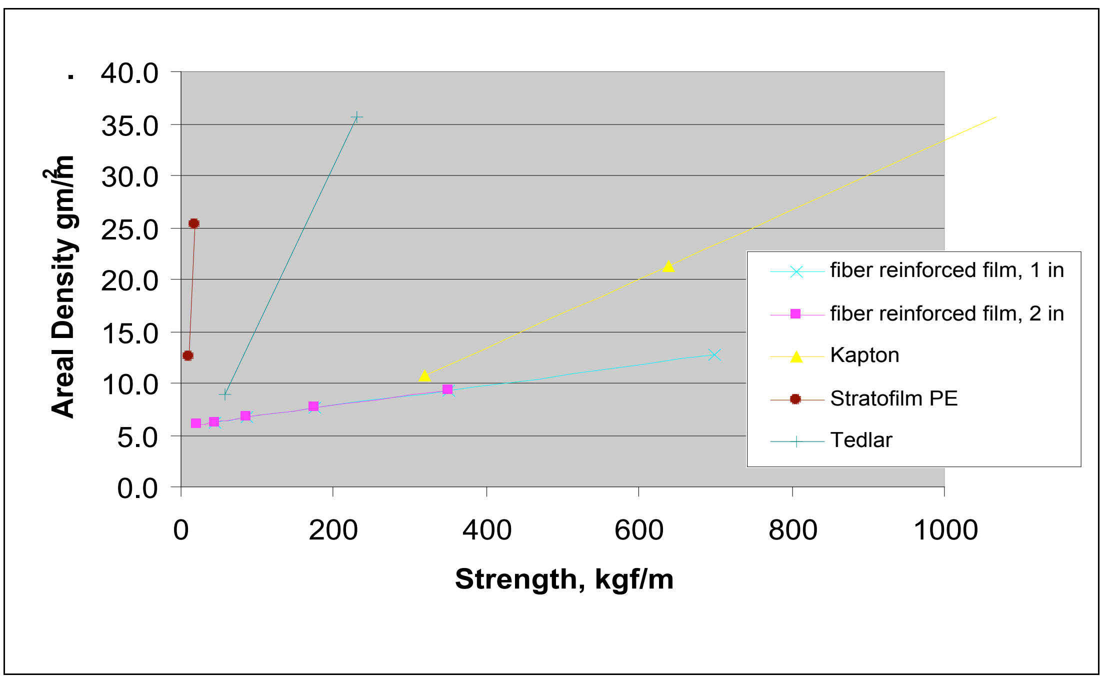


Figure 15 – Strength and Areal Density of Various Materials

It appears that both reinforced and un-reinforced film approaches are feasible. The advantage put forward for un-reinforced film, such as Tedlar, is that it stretches to absorb non-uniform or peak transient loading. A film reinforced by a high tenacity fiber, is lighter, dimensionally stable and damage tolerant. By damage tolerant we

mean that local damage does not propagate into a total failure and that the parachute can operate with significant distributed damage.

The final material selection warrants further study and discussion. We will conclude, for the purposes of this study, that materials exist with more than adequate strength and with an areal density of 7.5 gm/m^2.

Editor's Note: A subsequent comment was provided by Jack Jones at JPL regarding the use of Orcon fibers:

"We have tried the Orcon fiber reinforced mylar film (Fig 14) for several large balloon deployments (Diameter=15-20 meters, altittude = 35 km, descent speed = 50 m/sec). Orcon fibers are glued in only one direction, while the perpendicular threads are not glued. All balloons failed with the tearing occurring parallel to the glued lines. That is, the unglued lines did not stop tearing. Of course, the non-reinforced mylar also tore during deployment. All our materials were in the range of 10-15 gm/m2. We are finding the highest stress occurs when the balloon is partially full, and thus the speed is faster, which increases the dynamic pressure. The steady state stresses are well below these transient stresses." - Jack Jones 11/10/2005

4.2.2. Parachute Weight Estimation

Experience with conventional, but lightweight parachute construction indicates that a parachute assembly will weigh approximately 80% more than the base fabric weight. $M_{para} = 1.8 A_c \rho_A$, where A_C is the fabric constructed area, and ρ_A is the areal density of the base fabric. This includes a typical amount of reinforcing ape and webbing, in addition to stitching and suspension lines. A higher fidelity estimate requires a complete preliminary design and it is entirely possible that a careful design taking account of low opening forces will be substantially lighter.

4.2.3. Thermal Considerations

Whatever temperature the parachute has while inside the ascent package will change almost immediately to that of the outside atmosphere when the low density material is deployed into the airstreams.

Does radiation change the surface temperature much? The equilibrium temperature in vacuum with solar radiation of 15 W/m^2 and an emissivity of 0.9 is approximately 128°K. With an air temperature that is somewhat higher, 180-280°K, the film temperature of the inflated parachute in full sunlight will be slightly less than the air temperature (the surface radiates faster than the solar input). A reflective coating on the material may be beneficial for thermal reasons an also provide a large radar cross-section.

For material selection purposes, the range of 150-280°K is a good initial estimate. A more complete thermal analysis will need to take into account the different flow conditions inside and outside the canopy in estimating the convective heat transfer coefficients verses the radiative balance.

The low-temperature effects on the materials will be most important on deployment, where some materials may be stiffened and crack/fracture when rapidly unfolding. Some materials have a low temperature phase transition from amorphous to crystalline (glass transition) that can cause stiffening and cracking. Materials that have a history of use at low temperatures include polyethylene (e.g. Stratofilm), polyester (Mylar), polyimid (Kapton and Upilex) and polyvinylfluoride (Tedlar), although the operating temperature for Mega-Meso is lower than most available data.

4.2.4. Strengths of Materials

Specific Strength of Films

The following Table 17 summarizes the room-temperature characteristics of a number of candidate films. PBO is included for comparison purposes, but is not available at this time.

Table 17 - Specific Strength of Candidate Films

Material	Name	σ_{brk}	σ_{brk}	ε_{brk}	s.g.	SS
		kg/mm2	ksi		g/cc	m
Polyimid	Kapton	18	26	70%	1.42	12,689
Polyimid	Upilex	53	75	42%	1.47	36,091
PBO	NA	63	89	2%	1.54	40,950
Aramid	Mictron	56	79	31%	1.5	37,371
PEN	Teijin	28	40	90%	1.36	20,743
PVF	Tedlar	9.2	13	95%	1.4	6,549
PE Laminate	Stratofilm	0.70	1	?	0.97	727
Polyester	Mylar	20	28	116%	1.39	14,403

Specific Strength of Fibers

Specific strength of fibers can be calculated directly from tenacity or from the combination of tensile strength and density, depending on the way each manufacturer chooses to present their data.

Table 18 - Specific Strength of Candidate Fibers

Material	σ_{brk}	s.g.	Tenacity	SS_{break}
	ksi	g/cc	gpd	m
PBO	820	1.56	42	3.71E+05
K49	500	1.44	23.6	2.45E+05
K29	400	1.44	23	1.96E+05
Vectran	500	1.44	23	2.45E+05
Spectra	435	0.97	38	3.16E+05
M5	1378	1.7		5.72E+05

Suitability of Open Weave

Since the flow can be taken as continuum, based on both Kn and on Hoerner's interaction parameter, a laminar boundary layer will develop. If a fabric were porous enough to "swallow" the boundary layer before it develops, then we might look to the drag of the individual fiber bundles in normal flow. However, if we work with the assumption that the flow through the permeable fabric is slow enough to allow a laminar boundary layer to develop, then the parachute will have higher drag and we can analyze the flow through the fabric as viscous flow through a distribution of small orifices, driven by the local pressure difference across the fabric.

Another way to look at open weave fabric for this application is that we wish to reduce the areal density of the fabric by increasing the spacing of the fibers, but not so much that we loose the effect of mutual interference of the fiber bundles that creates more drag than the same collection of fibers would as individual drag elements. What is the optimum spacing?

Given that flow through the passages in the fabric is an "internal flow" problem, and that no research on flow through screens as a function of Reynolds number was easily found, we will treat this as flow through a very short pipe.

In the familiar pipe flow chart below, the laminar flow line is of interest. Even though the region of our interest lies off the chart to the left, and noting the dangers of extreme extrapolation, if we fit a function to the line, we find the following:

$$f = 45R_d^{-1}$$

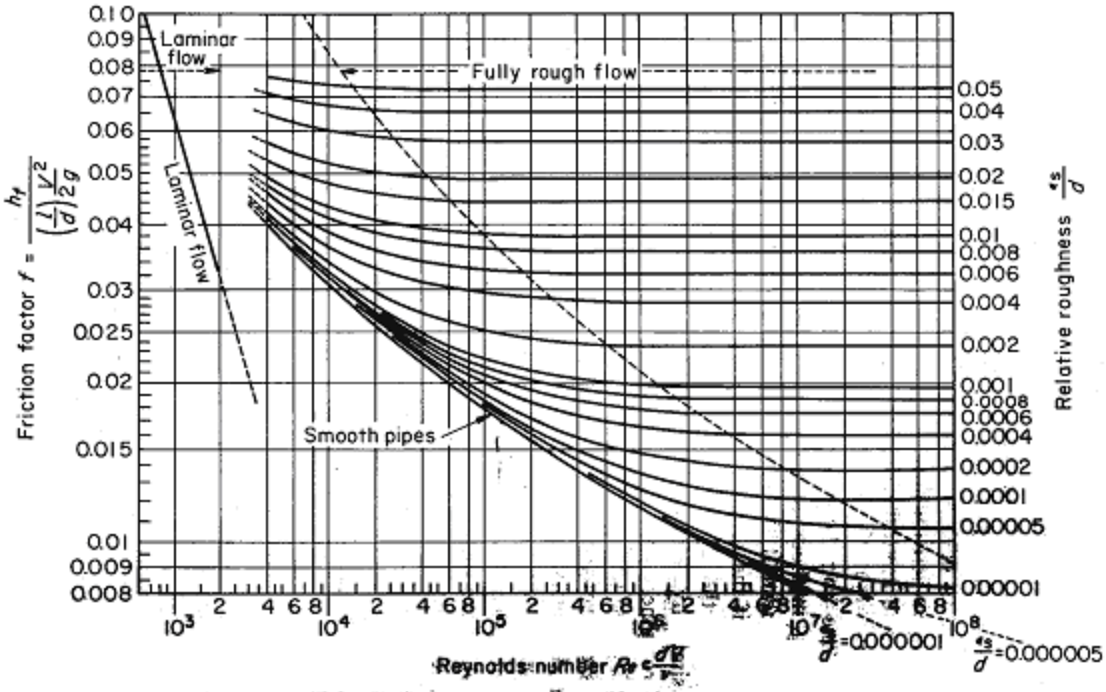


Fig. 5-5 *Friction coefficient as a function of Reynolds number for round pipes of various relative roughness ratios* ϵ_s/d. [L. F. Moody, "*Friction Factors for Pipe Flow*". Trans. ASME, *vol. 66, No. 8, 1944, p. 671.*]

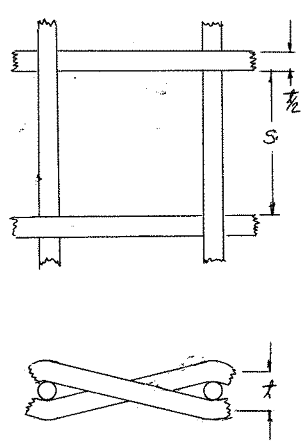
Figure 16 – Friction Coefficients as a Function of Reynolds Number

The exponent is consistent with laminar skin friction in general, so the result is not unreasonable.

Substituting the definition of Reynolds number, $R_d = \frac{dv}{\nu}$, in to the friction factor equation, $f = \frac{45\nu}{vd}$.

From Bernoulli, and assuming a uniform C_p of 1 across the parachute membrane, we can derive the ratio of the velocity through each fabric opening with dimension *s* and thickness *t*:

$$\frac{v}{V} = \sqrt{\frac{1}{1 + 45\frac{t}{s}\frac{\nu}{vs}}}$$



Hoerner defines a effective porosity (page 13-24) as the flow velocity through the fabric averaged over its area divided by the vertical descent velocity or airspeed.

$$\frac{w}{V} = \frac{w}{v}\frac{v}{V}$$

We already have the equation for v/V. The flow velocity through the fabric, w, is the average velocity over many unit cells of the fabric. $w = v\dfrac{s^2}{\left(s + \frac{t}{2}\right)^2}$, where $\frac{t}{2}$ is the yarn diameter.

The chart below illustrates effective porosity calculated by this method for plain weave fabric of 1500 denier yarn with openings in with weave, *s*, ranging from 0.01 to 0.10 inch.

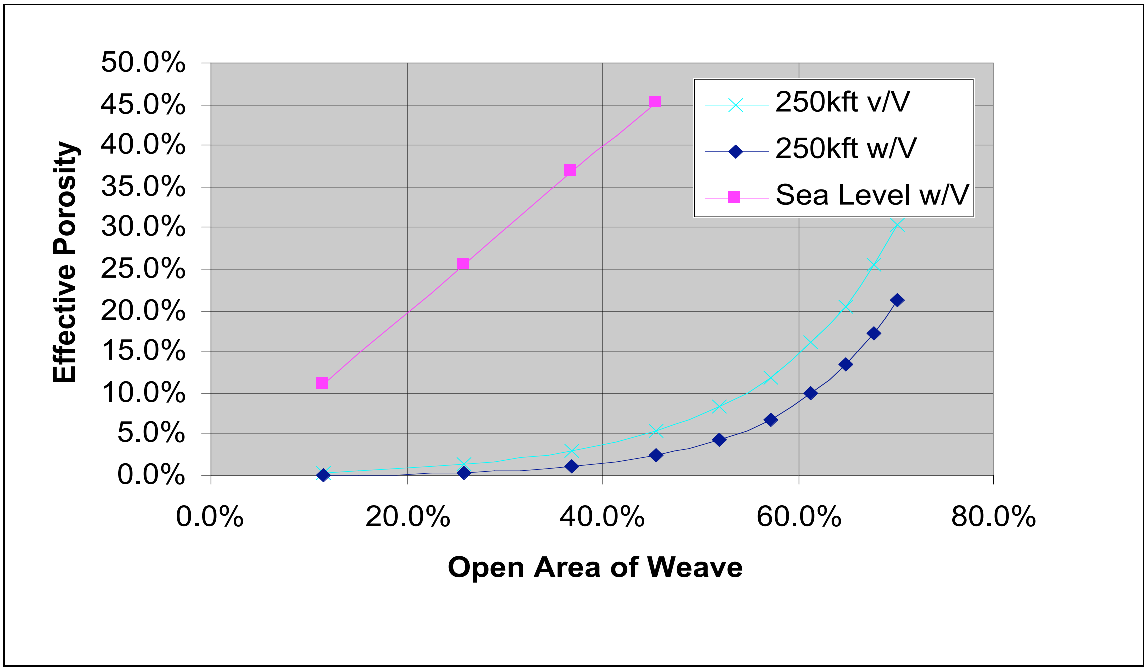


Figure 17 – Effective Porosity Calculations

The chart illustrates that at sea level, effective porosity is very nearly equal to the open area ratio of the fabric, while at 250,000 ft a fabric can be 60% open and have only 10% effective porosity – a consequence of high kinematic viscosity.

Enough porosity is needed for stability, but not so much that drag coefficient is sacrificed. We will assume a relative permeability flow velocity of about 10%, $\frac{w}{V} = 0.1$, along with enough geometric porosity to bring the total porosity to about 30%.

A 60% open fabric of 1500 denier Vectran would have the following properties:

Vectran Plain Weave		
61.4% Open Weave		
s=	0.07	in
yarn wt=	1500	denier
yarn dia=	0.0194	in
count=	11.2	ends/in
fab wt=	147	gm/m2
fab str=	29,359	kgf/m

This is clearly too heavy and stronger than needed, even at the most porous we estimate can be tolerated. Other examples were tried with lighter yarn, but with not much better results.

4.3. Parachute Descent Design

4.3.1. Effects of Reynolds Number

One effect of low Reynolds number is to decrease the permeability of fabrics. At the Reynolds numbers this parachute will experience, what would normally be considered a porous fabric will behave much as an impermeable film. This has two implications for the design:

- The much higher specific strength of fibers compared to films may favor the use of extremely lightweight fabrics.
- The low permeability of whatever material is chosen will push the design to a parachute type with geometric porosity for stability.

This report also looks at the feasibility of lightweight, open-weave fabrics for Mega-Meso. We find that such fabrics are still too heavy for this application and do not change the conclusion of the previous section.

4.3.2. Effects of Scale

Very lightly loaded parachute canopies tend to have higher drag coefficients. At sea level, the improvement is seen when descent velocities are below 20 f/s. The concept parachute is much more lightly loaded that this. We will assume for the purpose of estimating ballistic coefficient that drag coefficient increases approximately 20% for the type of parachute selected.

Another effect of scale is the number of suspension lines. The strength of a suspension line is based on an assumption about sharing peak loads between the lines. The higher the number of lines for the same total strength, the more vulnerable a parachute is to catastrophic damage if there is an inversion or other off-axis condition during opening. The number of suspension lines for a conventional "round" parachute will generally not be less than the skirt circumference divided by the width of the fabric. Cruciform, radial-cruciform, and tri-lobe types can be designed with fewer lines, but the fabric stress distribution in these types is less uniform.

Parachute as large as 100 m diameter may have been made, but the largest found in the literature is 190 ft diameter. Irvin Aerospace has made numerous drops, including clusters, with a 156 ft ringsail. The Russians are believed to have retarded a 27 ton atomic bomb with a single parachute canopy whose construction reportedly put a halt to the hosiery industry in Russia for a short period, but whose diameter is not reported.

There is nothing fundamentally impossible about manufacturing and deploying very large parachutes. Scientific balloons are of a similar size and face some of the same challenges and lessons learned in the ULDB program should be carefully reviewed for relevance to Mega-Meso. The key to meeting the challenges of very large size is a well controlled, symmetrical deployment and inflation.

4.3.3. Ballistic Coefficient

Ballistic coefficient is the key scale-independent parameter governing descent through the mesosphere.

We can estimate the ballistic coefficient as a function of diameter and base fabric, or film, weight.

$$B = \frac{M_{para} + M_{payload}}{C_D A} = \frac{1.8 \frac{\pi}{4} d^2 \rho_A + M_{payload}}{C_{Do} \frac{\pi}{4} d^2 \frac{A_o}{A_C}}$$

We will assume that for either a ringsail or tri-lobe, either of which is very lightly loaded and descending in a non-gliding mode, that the drag coefficient on the reference area is C_{Do}=1.1, and that the ratio of (constructed) fabric area to reference area is A_c/A_o=1.36.

The chart below shows the relationship between parachute diameter and ballistic coefficient for a payload mass of 50 kg.

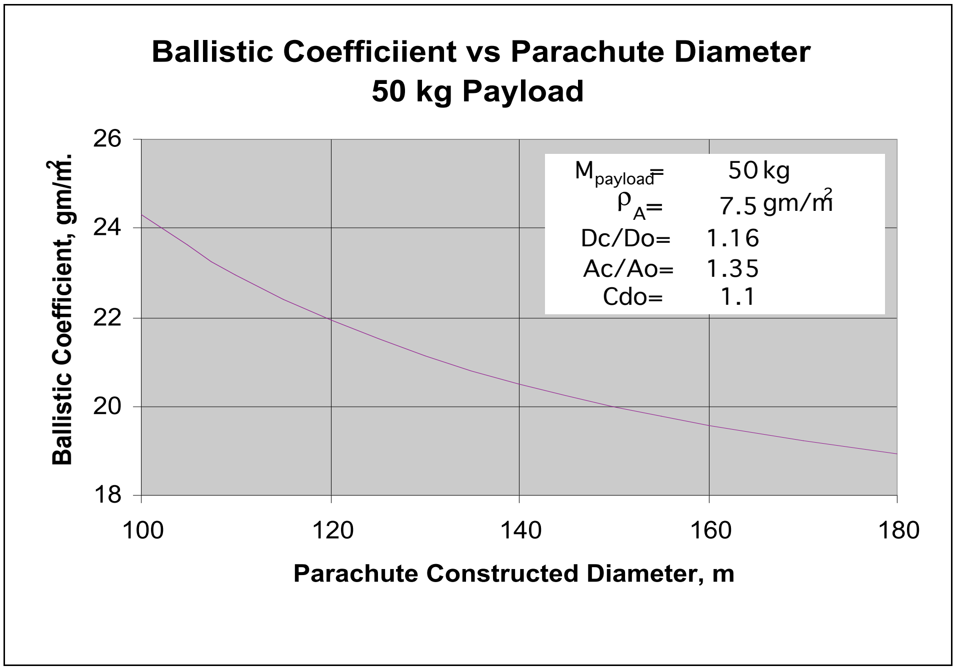


Figure 18 – Relationship between Parachute Diameter and Ballistic Coefficient

4.3.4. Descent Profile

The velocity to descend through a given density altitude is a function of ballistic coefficient. The chart below shows descent profiles for a range of ballistic coefficients. The lowest ballistic coefficient in the chart is for a minimum film thickness determined by the steady stress in the parachute canopy as suggested in reference 1. Our current estimate of minimum practical material areal density is 7.5 gm/m^2, which leads to a total ballistic coefficient of 20-24 gm/m^2, depending on parachute diameter.

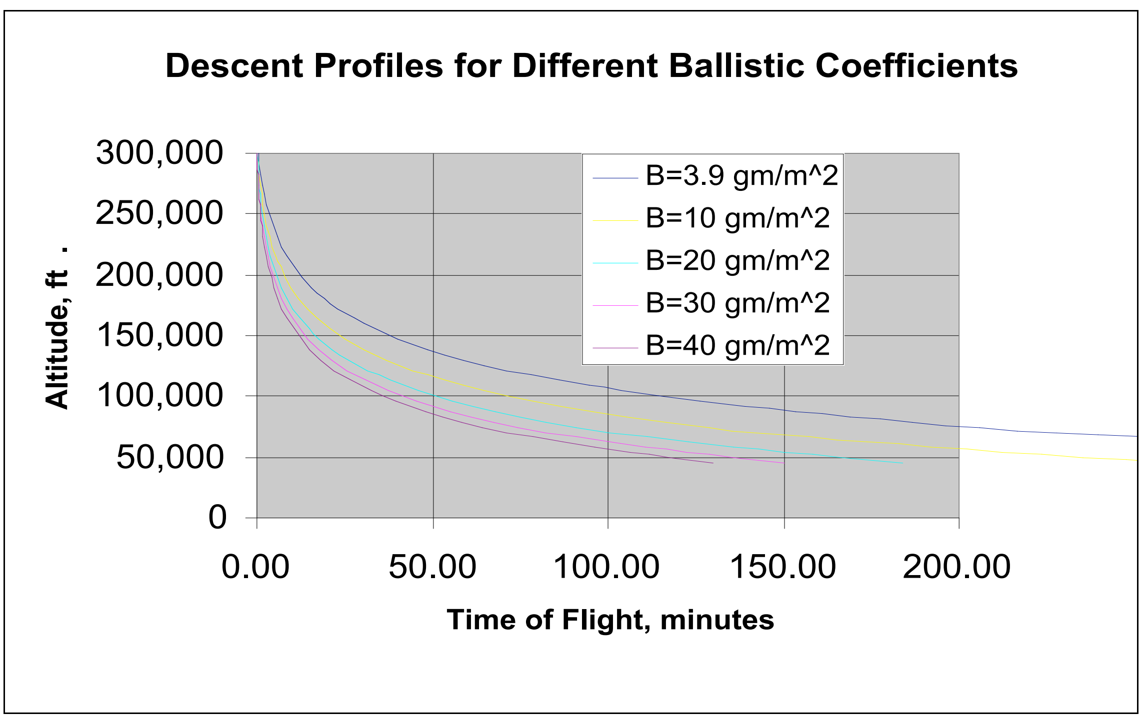


Figure 19 – Descent Profile

The same data is used to generate the chart below for time to descend from 300,000 ft to 150,000 ft. It appears that a useful time of flight of greater than 15 minutes is possible.

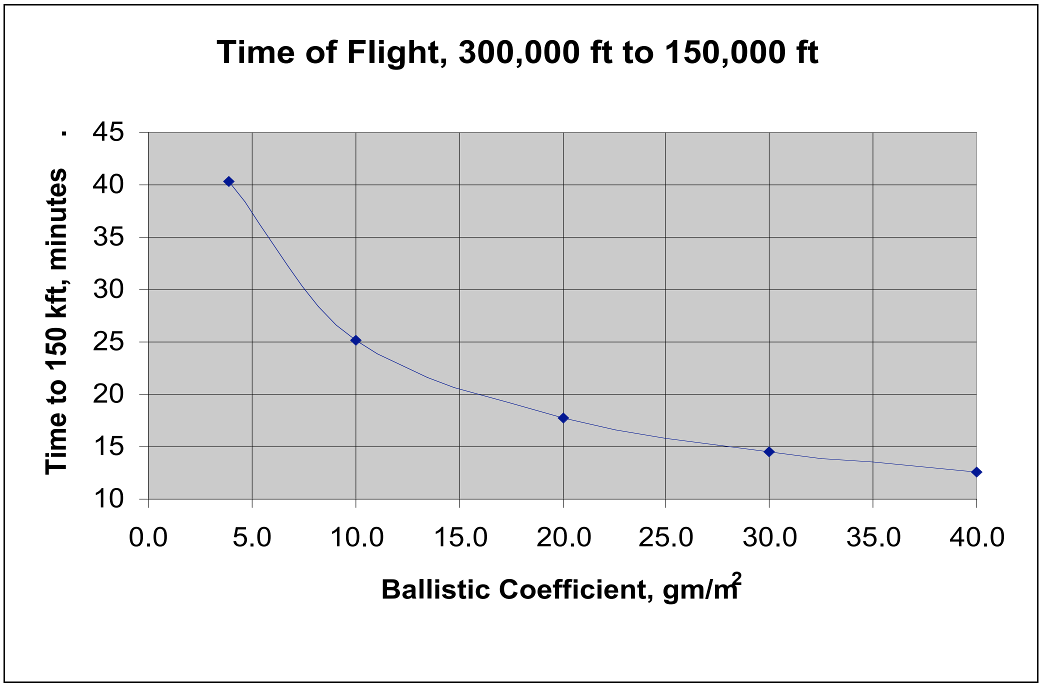


Figure 20 – Ballistic Coefficient Changes during Descent

4.3.5. Mach Number

Higher ballistic coefficient increases descent velocity. From the chart below, if the minimum practical ballistic coefficient is approximately 20 gm/m^2, it may be necessary to operate briefly in transonic flow, which will affect the parachute design.

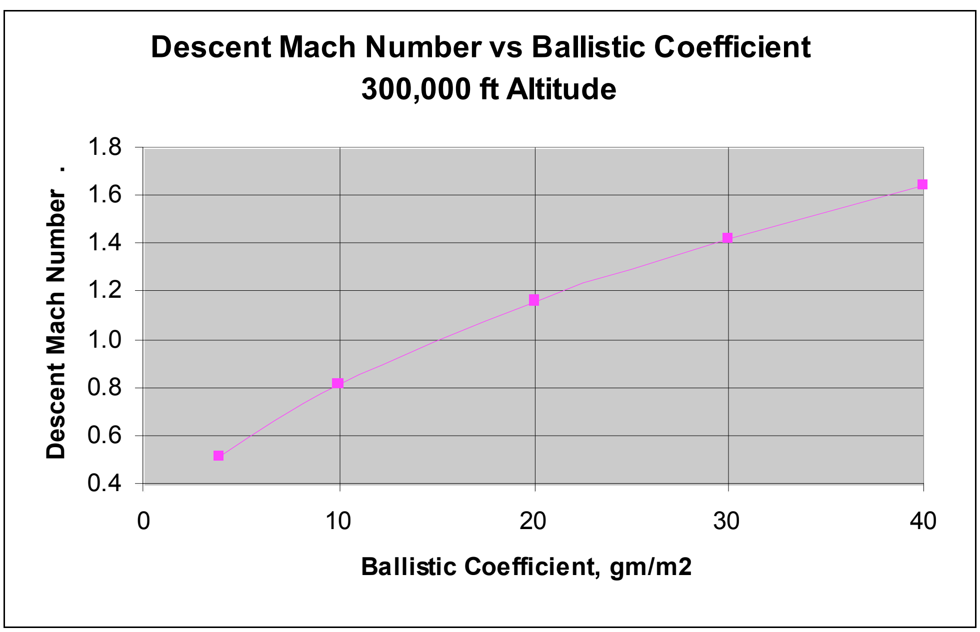


Figure 20 – Mach Number as a function of Ballistic Coefficient

Alternate strategies to reduce ballistic coefficient to less than 15 gm/m^2 would include at least one of the following:

- Lower areal density materials
- Lighter materials – suspension lines, etc.
- Gliding parachute

An example is shown in the chart below, in which we have increased drag coefficient from 1.1 to 2.0, representing a gliding type, and reduced the weight conversion factor from 1.8 to 1.5. A ballistic coefficient of less than 12 gm/m2 is possible with those improvements, which would keep Mach number less that 0.9 and the time of flight from 300,000 to 150,000 feet to about 23 minutes.

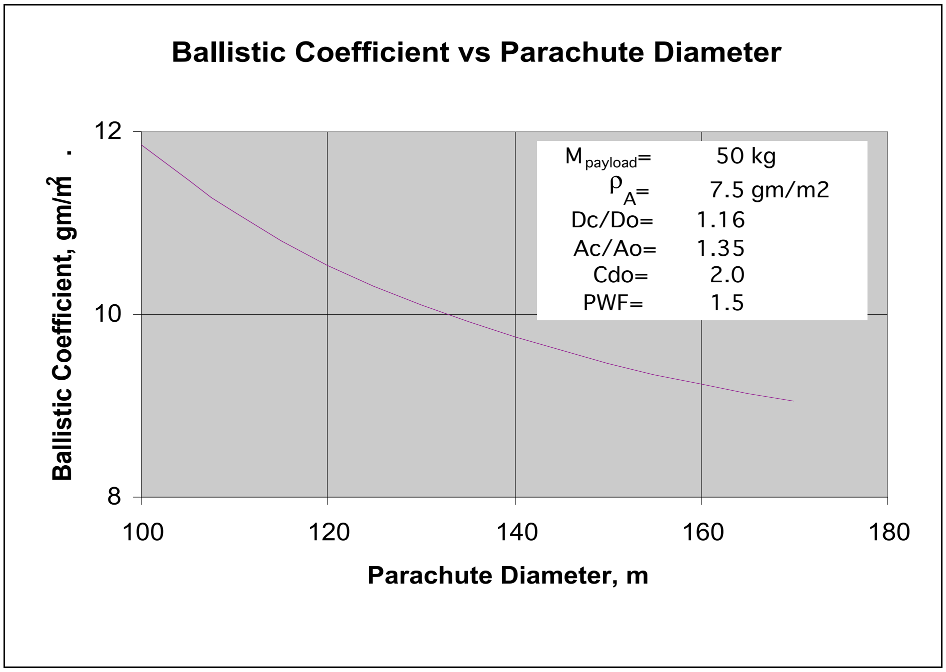


Figure 21 – Ballistic Coefficient Curve with Improved Drag Coefficient

4.4. Parachute Deployment Issues

4.4.1. Deployment and Opening Speed

The feasibility of using gossamer materials depends to a great extend on avoiding high transient loads, assuring that loads are evenly distributed, and avoiding destructive interactions while unfolding. All of these critical dependencies are related to deployment and opening.

The concept for limiting transient loads is to develop the full parachute area entirely while at a velocity less than the equilibrium descent velocity. While most parachutes decelerate through opening, this parachute will accelerate during and for a short time after opening.

Scientific balloon payload recovery parachutes are another example of this type of opening and provide some insight. It was thought that the method of pre-deploying by releasing an already-deployed parachute from a fitting below the balloon would result in the softest possible, reliable opening. Balloon payload recovery operations are, in fact, quite reliable. However, peak opening forces are not as low as they were once thought to be. The pre-deployed parachutes tend to rebound when released and have uncontrolled motion until enough airspeed is developed to start canopy inflation.

In order to determine the maximum inflation time and distance that assures no peak load greater than the fully open steady load, we will use the basis that full area development is completed by the time dynamic pressure reaches 50% of the equilibrium descent value.

Let us assume a maximum equilibrium descent velocity of Mach 0.8 at 300,000 ft, which is 726 ft/sec. Maximum velocity at full area development is then 513 ft/sec, which corresponds to a freefall of 4092 ft in 16 seconds. If the parachute is 100 m diameter (328 ft), we would normally assume that it would be fully open after traveling 15 diameters, or 4920 ft.

V_{z_eq}	-726ft/sec
V_{z_open}	-513ft/sec
ΔZ_{v_open}	4092ft
$T_{\Delta Z}$	15.94sec
D	328ft
Sopen	4920ft

What is the maximum horizontal velocity at apogee that is consistent with conditions for a low velocity opening as defined above? A trajectory was calculated with an initial horizontal velocity of 350 ft/sec. At the point where 4920 feet have been traveled from apogee, 2317 feet of altitude and the velocity is 520 ft/sec. A slightly higher horizontal velocity will be ok if deployment starts before apogee, but it should not exceed about 500 ft/sec for a low speed opening on the basis we have outlined.

We had anticipated the need for a device to accelerate opening by spreading the skirt. The above analysis does not prove the need for such a device as a method to reduce inflation time. The question becomes: can deployment be controlled using conventional methods, such as pilot chutes? This should be an area of further study through simulation. If there is not enough dynamic pressure for a pilot chute to pull the main parachute to line stretch, to open the deployment bag or sleeve, and to keep everything aligned as inflation starts, then inflatable devices to deploy the parachute and to spread its skirt will be necessary.

4.4.2. Deployment Sequence

The relatively low speed initial conditions for deployment and opening create the potential to open the Mega Meso Parachute without peak stress exceeding steady stress. This will be an objective of the system design. In order to achieve this objective, it will be necessary to satisfy the following conditions:

- Unfold parachute slowly, without high velocity sliding contact between surfaces;
- Maintain symmetry and alignment with the velocity vector;
- Provide a well-defined opening at the skirt at the beginning of the inflation;
- Complete inflation before reaching equilibrium descent velocity.

Slow, well sequenced unfolding is necessary in order to avoid damaging the gossamer materials by friction or mechanical contact. Even though dynamic pressure is very low, airspeed is high enough that, if a portion of the canopy were to accelerate to a high fraction of that airspeed while in contact with the surface of another portion, significant damage would occur. Failure to maintain symmetry and alignment with the velocity vector is an example of a condition almost guaranteed to cause the high velocity contact referred to above by partial inversion of the canopy.

The parachute inflation process is commonly observed to be somewhat inconsistent in time and distance, and is probably more so with very large parachutes. Vertigo and others have successfully demonstrated a method for making inflation distance much more repeatable (±0.1D) by tacking the skirt to a flexible ring that presents itself to the airstreams as an inlet to initiate parachute inflation. For Mega Meso, this can be accomplished with an inflatable ring not larger than 10% of the parachute constructed diameter. According to our estimates this will accomplish the final requirement of full canopy inflation before the system accelerates by gravity to the desired equilibrium descent velocity.

Inflatable devices will be useful for controlling deployment and opening. The inlet defining ring previously described would be a toroidal inflatable structure with attachment to the parachute in a way similar to a reefing line, with the similarity extending to the method of release.

An inflatable device will also be useful in providing a steady force, over a long stroke, and at a slow rate of extension for the purpose of unfolding the parachute while still in a protective sleeve. One concept for this inflatable deployment actuator is to integrate it into the sleeve, so that when the sleeve is opened and separates from the inflating parachute, the inflatable is discarded as well.

Deployment Sequence Concept

The initial deployment concept involves the use of a deployment stem. The stem would be an inflatable device. That is used to unpack the MegaMesoChute in an orderly fashion as required. The following sequence is proposed:

1.) Launch of sounding rocket, the initial rocket will be spin stabilized. It is suggested that a nose cone heat transfer analysis be performed to obtain a theoretical parachute deployment temperature

2.) Approaching apogee a de-spin operation is performed. This is typically done by a de-spin weight ejection system which changes the angular momentum. The attitude control system begins a pitch over maneuver (Figure 21).

3.) Nearing the sub-sonic apogee regime the nose cone is separated and the deployment stem inflation process begins (Figure 22)

4.) Deployment stem inflation process in progress (Figure 23)

5.) Deployment stem inflation process finalized. The stem is fully rigid, an accompanying/parallel parachute holding sleeve has been stretched out with the stem. The holding sleeve is made from lightweight cotton to minimize unfolding friction. . (Figure 24)

6.) The sleeve is opened, the megamesochute is separated from the deployment stem. The center torus begins inflation. The megamesochute separation is accomplished by detaching the ends and the inflating torus will push the stem structure away from the chute. (Figure 25)

7.) The torus continues to inflate and reaches ~10% of the diameter of the final chute and the megamesochute begins to open. (Figure 26)

8.) Torus separates as a result of megamesochute opening, the megamesochute continues to open (Figure 27)

9.) The megamesochute completes opening. (Figure 28)

10.) The final deployed Mega Meso Chute (Figures 29) and MegaMesoChute size comparison (Figure 30)

The megamesochute sequence was modeled using Martin Schweiger's Orbiter 2005 available at www.orbitersim.com. The Orbiter simulator uses a standard atmosphere model and very closely simulates the calculated mesospheric behavior of the megamesochute. The simulations may be a topic of future work.

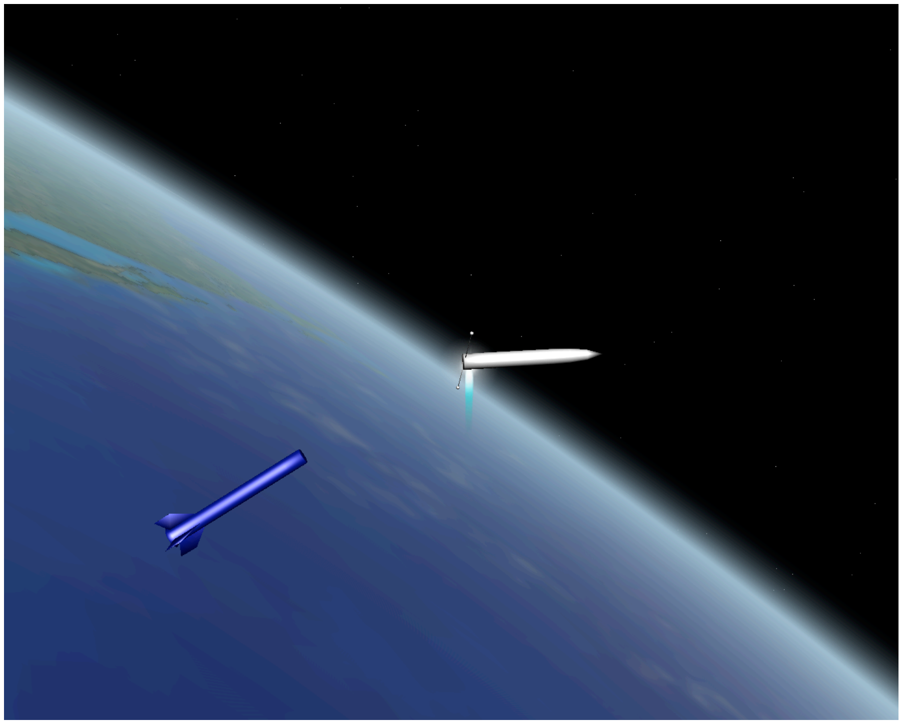


Figure 21 - Nose cone separation, de-spin weights deployed, and attitude control system begins pitch over.

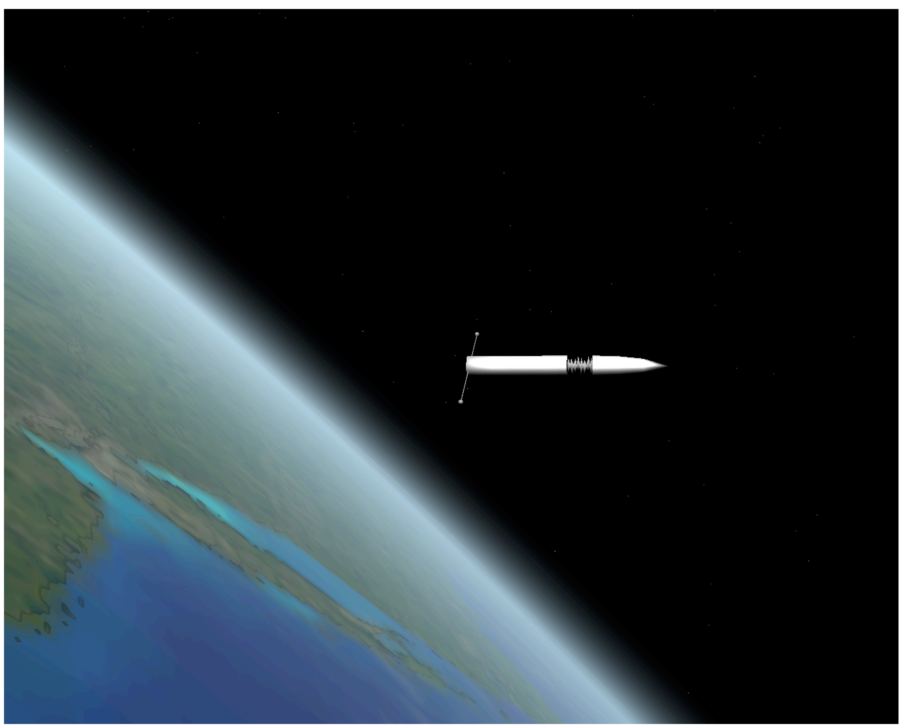


Figure 22 - Stem deployment process

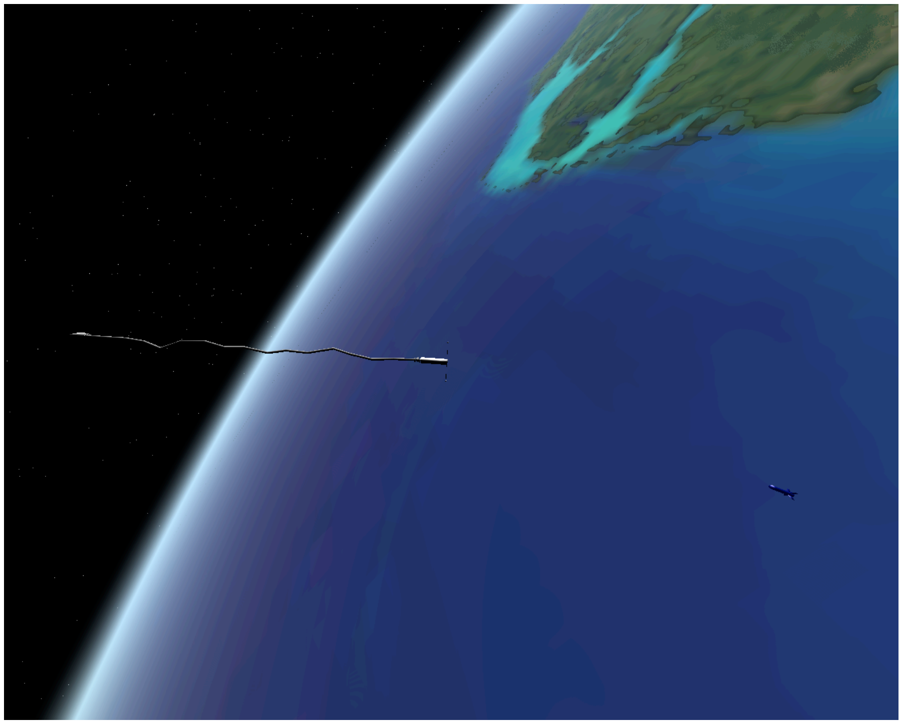


Figure 23 - Stem deployment continues at 80 kilometers altitude

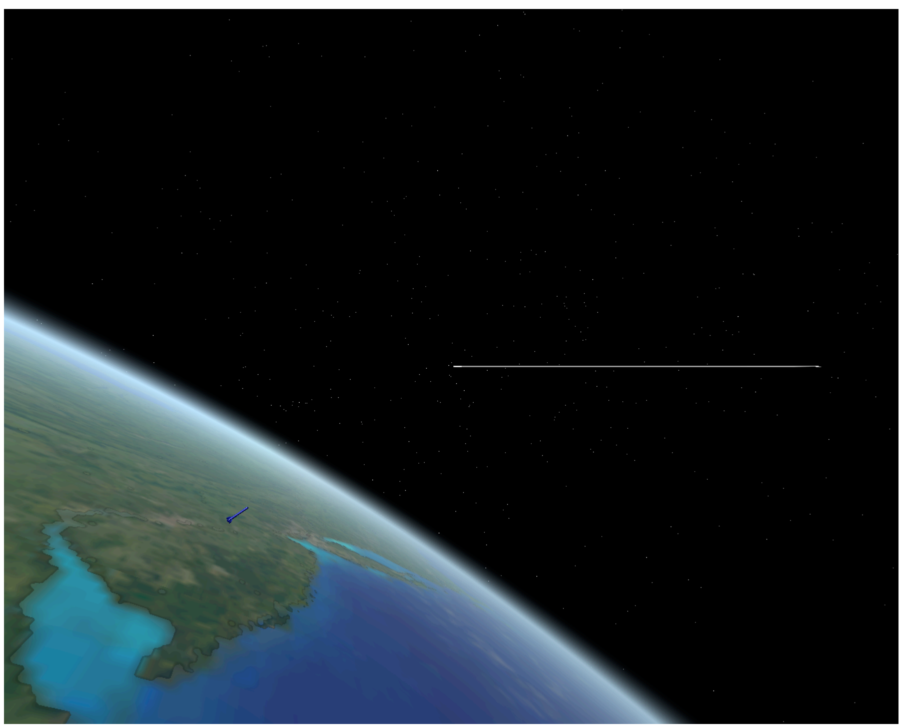


Figure 24 – Stem fully deployed, sleeve container is opened and torus inflation begins

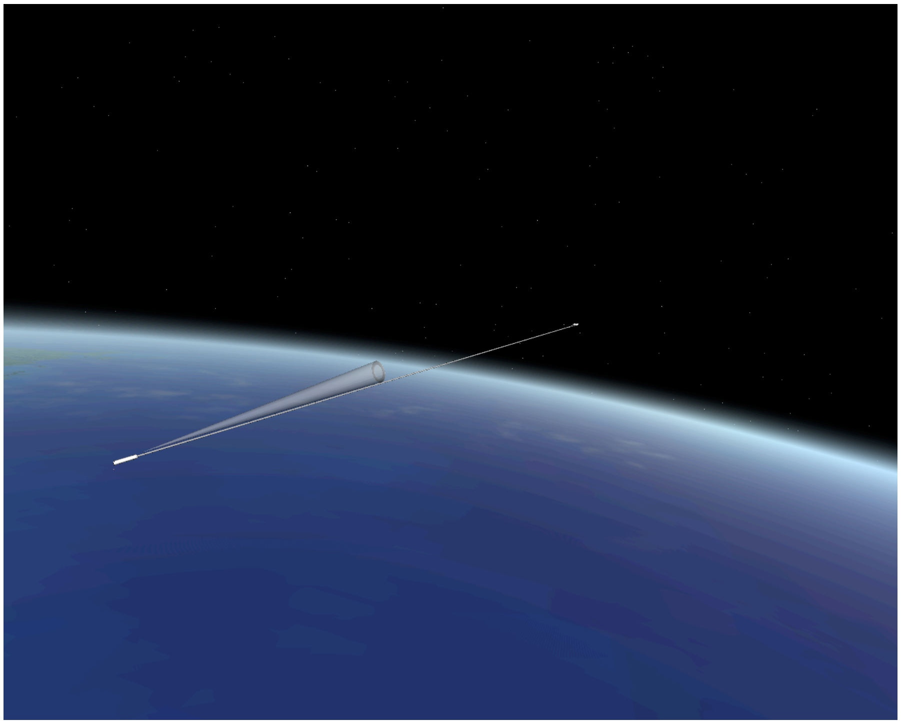


Figure 25 - Torus inflation continues and separation of stem continues, the megamesochute begins to open.

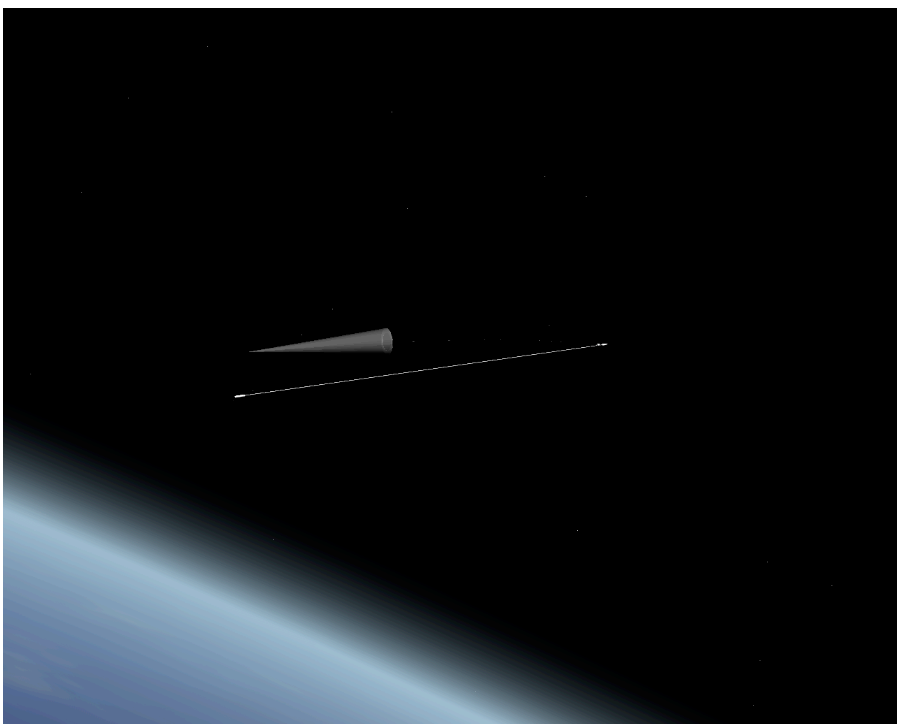


Figure 26 - Torus inflation continues and separation of stem continues.

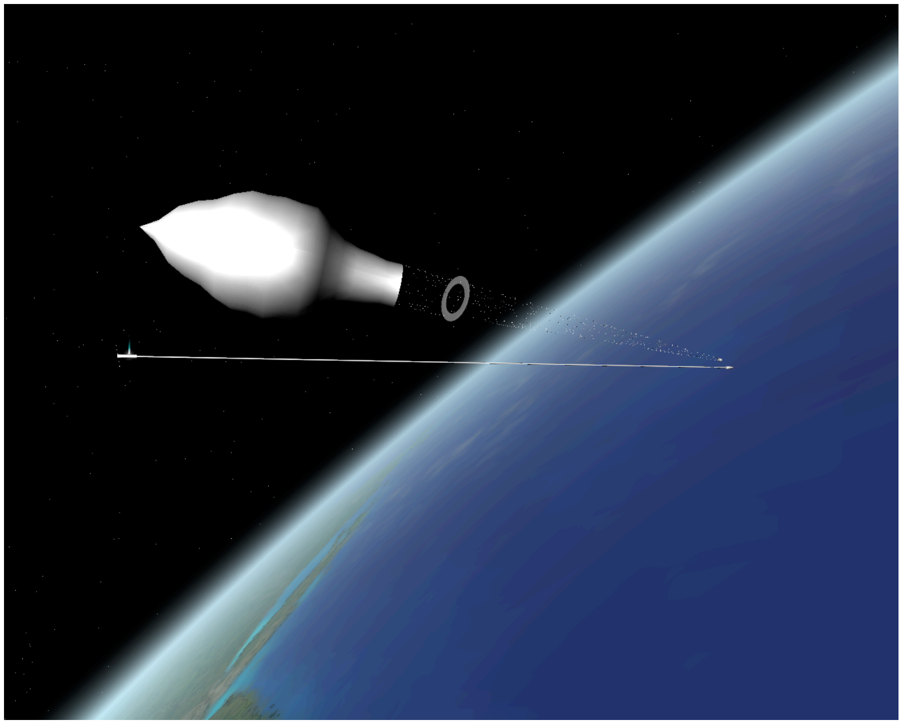


Figure 27 – MegaMesoChute continues to open.

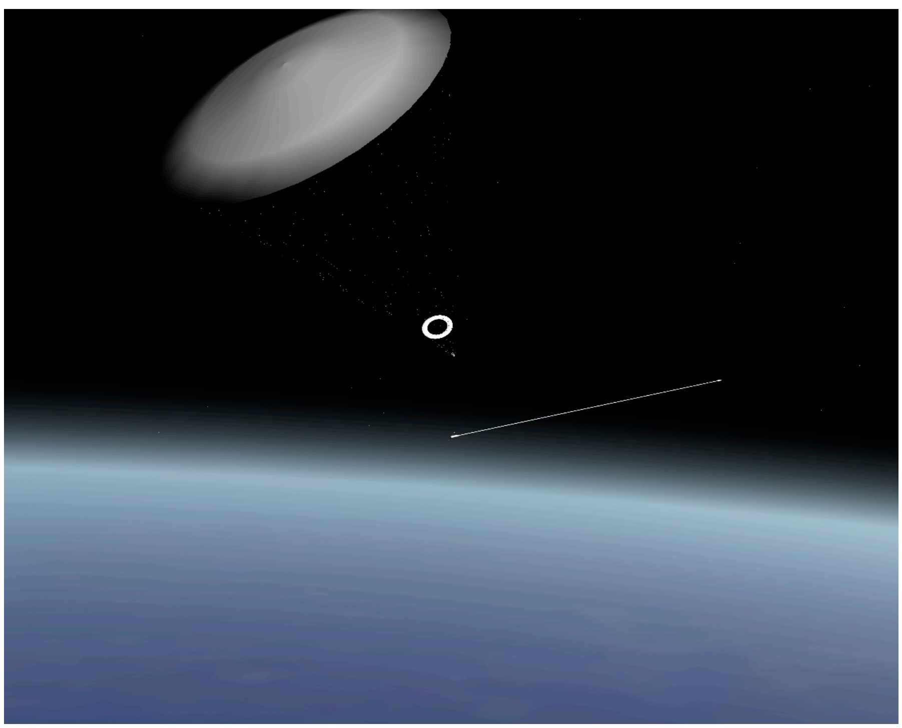


Figure 28 - MegaMesoChute completes opening.

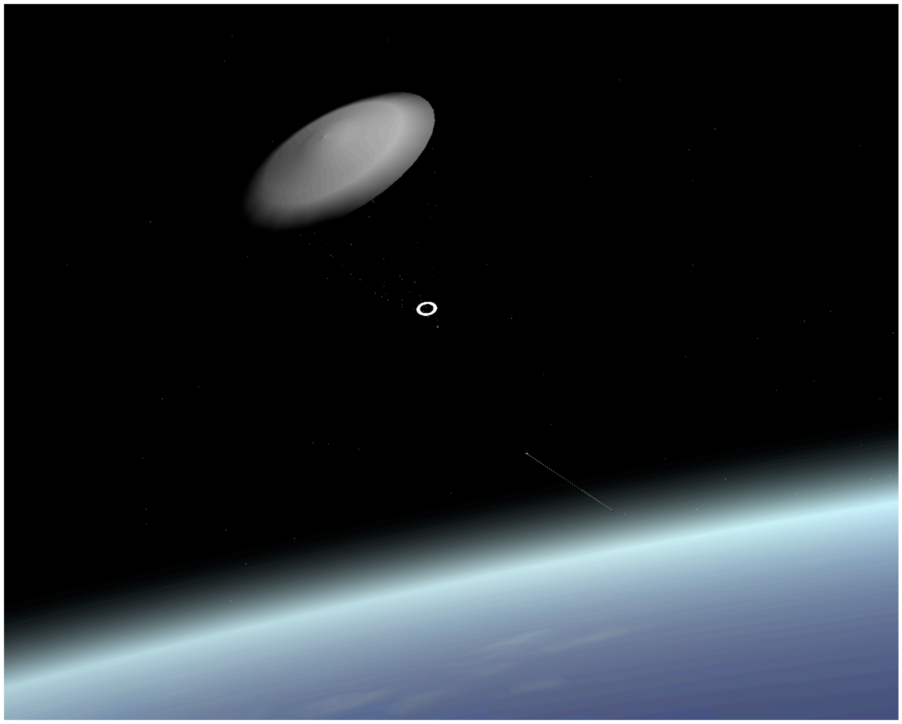


Figure 29 - MegaMesoChute responds to atmosphere, deployment stem and rocket fall away.

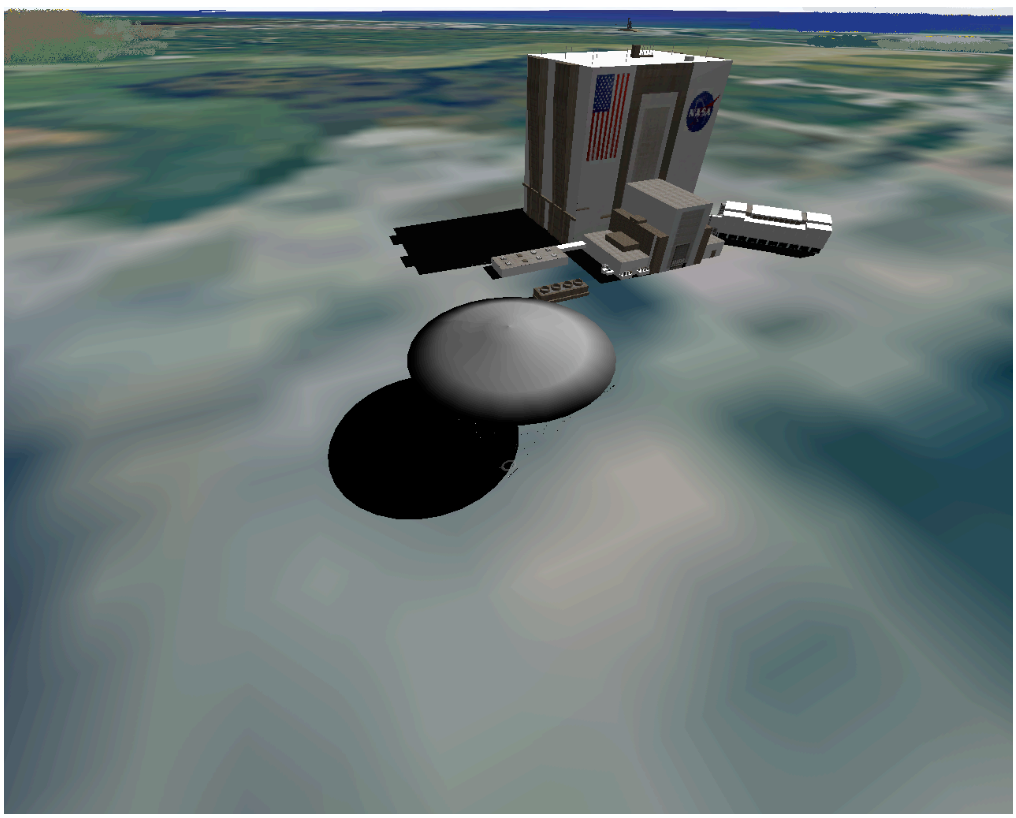


Figure 30 - 400’ diameter MegaMesoChute size comparison to vertical assembly building at Kennedy Spacecraft Center

4.4.3. Guidance

It is possible to guide either or both of the Mega Parachute and the recovery parachute. Reasons for guiding the Mega Chute would include keeping the system in controlled range airspace, for horizontal position holding for a payload that may need to remain over a position on the ground, or for maneuvering to enhance the operation of a particular sensor. Reasons for guiding the recovery parachute include keeping the system in controlled airspace, landing at a particular location for payload recovery, or to enable mid-air retrieval.

Parachute guidance relies on the ability to glide. Two was this have been implemented are glide-on command and fixed gliding geometry with steering. Glide on command systems do not glide until commanded to do so, and then glide on a particular selected heading. Such systems have good response to control input, and can reverse direction quickly, resulting in high terminal landing accuracy. Glide-and-steer systems glide at all times while in flight and require a steering input from steering actuators to change heading. Gliding parachutes are sometimes used without active controls, in which case a slow turn is rigged into the canopy to prevent long glides off the assigned range or additional intercept distance for the retrieving helicopter.

For low altitude recovery use, a parachute is the preferred, and, for mid-air retrieval, the necessary, parachute type. For the Mega Parachute, a parafoil would be too heavy and a single-surface gliding type will be necessary. Single surface gliding parachutes range from non-gliding round parachutes modified with some form of asymmetry, to Rogallo types , studied extensively (but not selected) for Apollo. Rogallo types have high a higher glide ratio, but might be more difficult to deploy and open without damage.

4.5. Additional Design Criteria

4.5.1. Estimated Weight of Inflation Gas

In order to promote the initial opening of the mega-meso chute, it is proposed that the stem and torus system members will be inflated with a gas. The initial calculations use the ideal gas law, recognizing that the low density nature of the final inflated device may be well beyond the practical limits of this equation. Most common references indicate that this relation breaks down only in the high pressure region or low temperature due to Van der Waals forces.

$$PV = m\frac{\overline{R}}{\overline{\overline{M}}}T$$

It is noted that a density of 2e19 molecules per cubic centimeter is a possible limit to this equation due to the fact that this is considered the limit where a gas is considered rarified (References: *Fundamentals of Aerodynamics* 3rd Edition, Chapter 14, John D. Anderson Jr., Mcgraw-Hill, 2001 and Gas Dynamics, 2nd Edition, James E.A. John, Prentice Hall, 1984,ISBN 0-205-08014-6)

The calculation uses the original configuration of the meso-chute and assumes the stem is 153 meters long (500ft) and .3048 m in diameter. (1 foot). Similarly, the torus is assumed to have 61 meter radius (200ft) and to be .3048 m in diameter. (1 foot). The torus calculation also uses a simple linear approximation of volume, not an inner and outer torus radius volume calculation. The original configuration (initial concept) has the torus at the rim of the mega meso chute, whereas subsequent design iterations have a smaller torus of as small as 10 foot in diameter which eventually detaches itself from a fully expanded/dilated rim. However, the use of the original configuration gives the most conservative estimate.

The initial inflation pressure was taken from the inflation pressures used in the Ultra Long Endurance Balloon (ULDB) program as a starting estimation point. The high altitude balloon numbers estimate a differential pressure at 170,000 feet, whereas the mega meso chute will be inflated at 350,000 feet which is closer a vacuum.

Several common gases where examined; Hydrogen, Helium, Nitrogen and air. The temperature above 53 Km is about 280 K and cools to approximately 165 K to an isothermal layer at 80 Km and remains at this temperature until about 90 Km, for this point on it becomes a standard planetary exponential model. The static temperature used was

165 K, which would be the approximate altitude of deployment. It is conjectured that the thermal radiative heat loss would be within seconds for a thin membrane and thus the 165 K number is a good starting point.

Table 19 - Estimation of Possible Inflation Gas Weight Range

Gas	$\overline{M}$	Kg @ .01 psi 68.95 N/m2	Kg @ 0.225 psi 1551 N/m2
Hydrogen	2.016	0.0039	0.089
Helium	4.003	0.0078	0.176
Nitrogen	28.014	0.055	1.23
Air	28.987	0.056	1.28

Thus Table 19 demonstrates that a possible greatest value of weight would be approximately 1.28 kg. A container for this gas was then selected. The container was a TAVCO cylinder which weighs approximately 1 pound (.45 kg). The volume of this contain was 35 cubic inches (573.5 cm3 or 573.5 mL) and was rated at 3000 psi (20 MegaPascals). Thus at 1.28 kg@20MegaPascals air would require 323 cubic inches and thus approximately 10 of these type cylinders in order to accomplish the full 0.225 psi of air. The minimum amount of air required would be 0.056 kg, which would require a volume of 14.36 cubic inches. Thus the minimum would be less than one TAVCO cylinder and the estimated range of weight for the inflation system using compressed gas would be between 6 kgs and say, 1 kg. In addition, the density of final expanded gases falls in the range between 3.17E*14 to 7.84e*15 molecules per cubic centimeter. Thus the final numbers violate criteria for using ideal gas equation and the gas inside the inflated structure. These conclusions lead us to investigate alternative methods.

4.5.2. Expansion of Compressed Gas

In addition to the problems with weight and volume using a compressed gas, there is also the consideration of the temperature of an expanding gas. It is possible that the expanding gas will cause and enormous amount of cooling. Thus it was necessary to touch upon the amount of cooling that may occur. The following equation was used which also assumes a ideal gas. This was also used as a starting point, understanding that the ideal gas law may not be accurate in the rarified region. For a perfect gas with constant specific heats that undergo an isentropic change;

$$\frac{T_2}{T_1} = \left[\frac{P_2}{P_1}\right]^{\frac{(\gamma-1)}{\gamma}}$$

Thus for a beginning compressed air temperature of 298 K, and pressures starting at 3000 psi and ending at 0.225 psi, and ratio of specific heats for air is approximately 1.4, the final temperature is about 3 K. The expanding air would therefore have the possibility of liquefying and clogging the valve (a pyrotechnic valve was considered for this application). The condensating gas droplets could also possibly interfere with the inflation and the speed of the inflation. These complications suggest that other solutions besides compressed gas should be pursued.

4.5.3. Gas Generator

There are several forms of gas generators, the most commonly used gas generator is the airbag which uses sodium azide, NaN_3.

Sodium azide will decompose rapidly into raw sodium and nitrogen, the sodium typically combines with water vapor in the to form sodium hydroxide. A pervious calculation indicated that it would require approximately 1.23 kgs of nitrogen to inflate the stem and torus of the mega-meso chute to a pressure of 0.225 psi. The amount of sodium azide required to generate this amount of nitrogen is calculated to be approximately 2.0 kgs. This is a simple first past calculation. The orderly deployment of the mega-meso chute may require sequential initiation of gas generator charges. The final estimate given for the inflation system was a conservative 5 kg.

4.5.4. Speed of Inflation

The literature suggests that airbags inflate at a speed of about 300 km per hour and reach full deployment in approximately 30 milliseconds. These numbers were used to arrive at a possible quickest deployment speed. It is recognized that an airbag is constructed of considerably thicker membranes plastic (Kevlar) and operates at a different temperature range. However these numbers give forth the ideal that the final deployment speed of the megamesochute is within in the range of practical realization. Using a speed of 300 km/h, the 152 meter long stem, the longest element of the system, can be deployed in 1.7 seconds. Since the arc of the subsonic apogee is about a minute, this demonstrates that the subsonic deployment may be possible. The next calculation assumes that an airbag has a volume of 0.075 cubic meters. Using this volume and the 30 millisecond airbag deployment time, an 11 cubic meter volume (stem) could be deployed in approximately 4 seconds. Once again, recognizing that the air bag material is much thicker, the calculations indicate that subsonic deployment is within a feasible range.

4.5.5. Temperature of Material Exposed to Mesosphere

Radiative Modeling

There is some question as to whether the mega meso chute material, deployed in the mesosphere (temperature of 165 K), will fall below the material's glass transition point (for LDPE 148 K) and thus the chute will shatter or crack during deployment. The problem being that the working margin of ~20K is slim and this coupled with the fact that the glass transition curve is not linear and the transition point is not precisely defined and depends on manufacturing quality and the presence of additives.

In order to attempt to answer this question, a finite element time dependent thermal model was constructed. The preliminary model under consideration was thermal radiative only, assuming that the density of air was so low that conductive thermal transfer was negligible. The convective thermal transfer was not modeled.

The equation used was the time dependent heat transfer equation:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \bullet (k \nabla T)$$

Where the values in Table 20 listed below were used.

Table 20 – Numerical Values used for Radiative Modeling

Materials	Specific Heat Capacity (C_p) J/kg*K	Thermal Conductivity (k) W/m*K	Density (ρ) Kg/m3	Initial Temperature Kelvin
LDPE	1200	0.3	1000	293
Air @ 80km	1005	0.0168	1E-05	165

The emissivity (ε) of 0.6 was used for the plastic and σ is 5.67 X 10^{-8} W/m^2*K^4. The model was a 2 dimensional area which was 100.0e-6 meters tall and 4.2e-6 meters thick, the top and bottom boundaries were considered thermally insulated. In the above equation, there is no internal heat generation and the heat will be supplied via the boundary conditions. The plastic was assumed opaque, although LDPE in pure form is transparent, but opaque LDPE is available and the additives could affect the glass transition point. For the model, the plastic could either freeze and shatter, or heat up and melt. The introductive calculation was weighed towards using an opaque material to take advantage of the solar heating. The model was also assumed to be launched at the equator at mid-noon.

The model includes the following heat inputs:

1.) From the sun (I_{Solar}, 1367 W/m^2) with a reflection of 30% from the plastic facing the sun gives a heat input of 960 W/m^2.

2.) On the Earth facing side, A 30% reflection from the earth's albedo, ($I_{Earth\ albedo}$) including 30% plastic reflection gives 0.3*0.3*I_{Solar} = 287 W/m^2

3.) Also on the Earth facing side, the earth's blackbody temperature (254K) or otherwise called the earth's infrared temperature ($I_{Earth\ IR}$) and 30% of this energy reflected by the plastic gives:

$$\text{Total } I_{Earth\ IR} \text{ and } 0.3 I_{Earth\ IR\ reflected\ from\ plastic} = \sigma * (254\ K)^4 * 0.7 = 165\ W/m^2$$

The model assumed 30% reflectivity on both sides of the LDPE sheet. The plastic is assumed to be at 293K at launch and during deployment, although more extensive modeling will be required in the future to model the temperature changes during deployment. Thus, the plastic will have a blackbody temperature of 293K initially and is assumed to radiate towards a 254 K sink on the earth facing side and a 3K sink on the sun facing side, assuming that the sun is a point source and the majority of the sink is at 3K space background temperature. The boundary conditions are therefore:

$$n \bullet (k\nabla T) = 960 + 0.6\sigma(3^4 - T^4) \text{ (Sun facing side)}$$

$$n \bullet (k\nabla T) = 452 + 0.6\sigma(254^4 - T^4) \text{ (Earth facing side)}$$

And the rest of the boundaries were insulated.

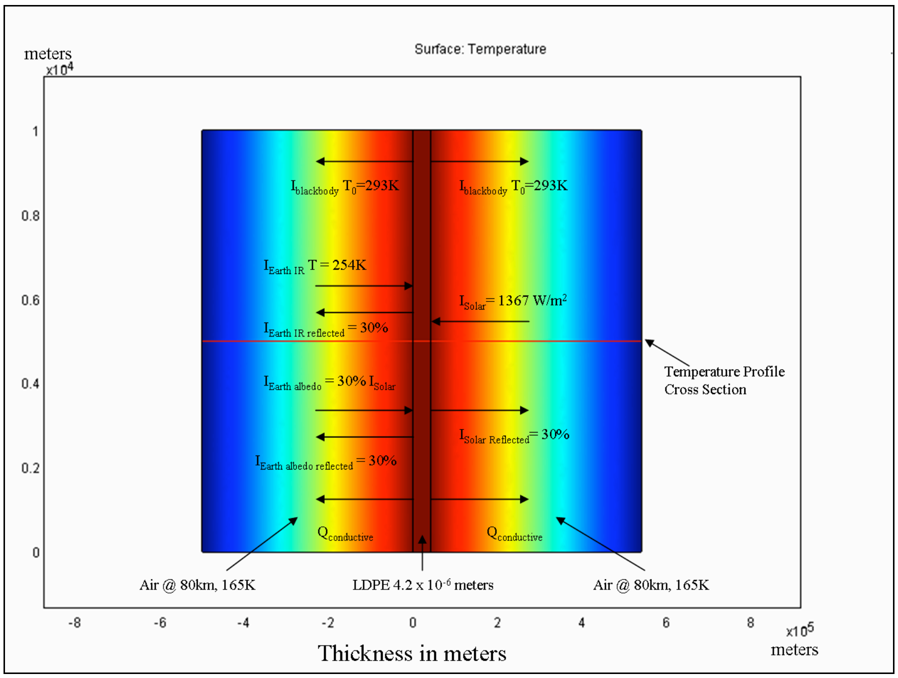


Figure 31 - Thermal Model of Low Density Polyethylene (LDPE) in the mesosphere. The final model includes radiative and heat conduction effects. The LDPE is initially at 293 K.

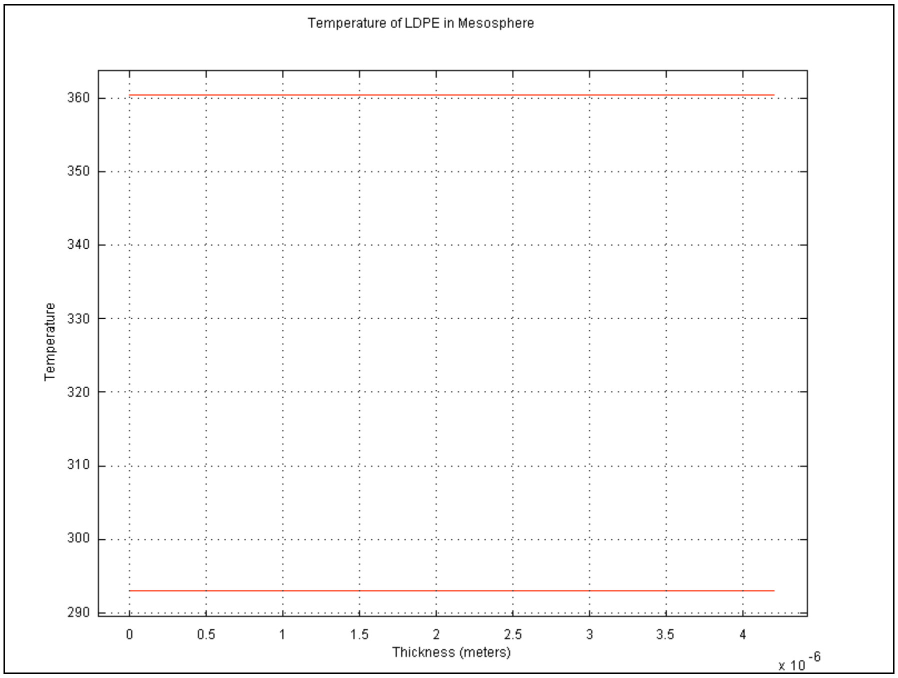


Figure 32 - The radiative and conductive model showing a temperature rise, the lower line is at time zero. After 10 seconds the LDPE sheet reaches an equilibrium temperature of 360 K (67 C).

Conductive Modeling Considerations

The following analysis is based on the chapter "Heat transfer of Residual Gases" which is in the book entitled "Cryogenics, by T.M. Flynn, p. 370, 1996, ISBN 0-8247-9724-8". For this analysis it is assumed that the density and pressure of the gases at 80 km are in the free molecular regime (.1 mm Hg to .01 mm Hg as defined by the reference). The density at 80 km is approximately 1 x 10^{-5} kg/m^3 , the pressure is 0.868 N/m^2 (0.00651 mm Hg, 0.651 μ m Hg), and thus the mean free path length is about 4 x 10^{-3} meters.

Using the equation on page 372 developed by Corruccini (1957, 1958)

$$\dot{Q}_{gc} = 0.0159\alpha P(T_2 - T_1)$$

Where $\dot{Q}_{gc}$ is in W/cm^2 and α , the accommodation factor, is assumed to be one. The constant used was on Table 7-4, page 373 of the reference. The final boundary conditions are developed:

$$n \bullet (k\nabla T) = 960 + 1.035(165K - T) + 0.6\sigma(3^4 - T^4)$$ (Sun facing side)

$$n \bullet (k\nabla T) = 452 + 1.035(165K - T) + 0.6\sigma(254^4 - T^4)$$ (Earth facing side).

Model with no Solar Inputs

The initial model has several heat inputs. The model simulation was then executed without solar heat input, and without Earth albedo input. The Earth's blackbody radiation was left as the only heat input. The final temperature was approximately 226.5 K after 30 seconds (Figures 33 a and b below).

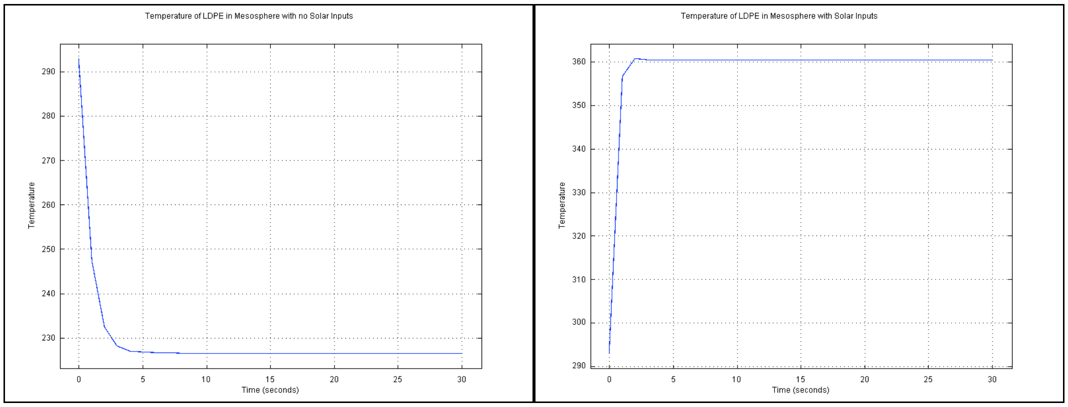


Figure 33 - (a) The figure on the left is the thermal model with no solar inputs and has only the earth's blackbody (infrared radiation) and reaches a final temperature of 226.5 K after 30 seconds. **(b)** The figure on the right includes solar input and earth's albedo as inputs and reaches a temperature of 360K after 30 seconds. Both models were initialized at 293 K

Thermal Modeling Conclusions

A 4.2 micron LDPE sheet was thermally modeled (assuming some IR absorption) using solar radiative effects and heat conduction effects in the mesosphere. It was found that the heating from the sun causes the LDPE sheet to reach a temperature of 360 K, and with no solar inputs the earth's blackbody radiation supplies heat to maintain the mega meso chute temperature at 225 K.

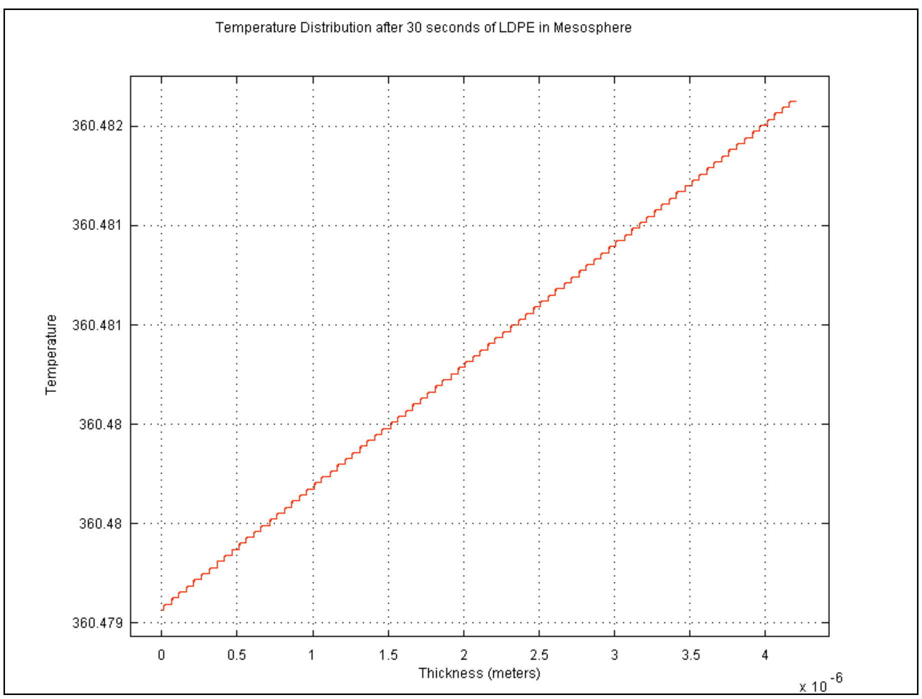


Figure 34 - Cross Section cut of LDPE thermal model exposed to the mesosphere. The red line is the temperature profile after 30 seconds. The model predicts that the LDPE will quickly reach a temperature of about 360K when the meso chute is deployed at mid-noon at the equator.

5. Mission Cost Analysis

DISCLAIMER: SCOPING STUDY
The cost estimates are as preliminary as the strawman vehicle design, and don't include the usual >30% cost reserves.

5.1. Cost Assumptions and Guidelines

The MegaChute study is to launch a sounding rocket above the mesosphere and deploy a parachute and science package to take science measurements within the 50 to 85km range. The purpose of the Team X study was to develop a scientific payload and a resulting MegaChute program.

- Three options were evaluated during the design session:
  - Case 1 is a baseline mission to prove the capability of the parachute and mission. The parachute is approximately 80m diameter. Case 1 includes the total project costs over the 2 year mission.
  - Case 2 is a follow-on mission to Case 1 that includes the same instrument suite, but includes higher altitude, guidance and a final descent stage that requires a larger launch vehicle. The larger mission requires a parachute of approximately 130m diameter. Case 2 includes the total project costs over the 2 year mission.
  - Case 3 is a more advanced project that includes a larger number of instruments (many different instruments from Case 1 and 2). The mission requires the larger launch vehicle and a parachute of approximately 200m diameter. Case 3 includes the total project costs over the 3 year mission. All costs are reported in FY 2005 $K.
- An estimate of the project lengths of each Case were determined by the Science subsystem
  - Case 1 and 2 are 24 months long for the entire project (costs are estimated for the entire project)
  - Case 3 is 36 months long for the entire project (costs are estimated for the entire project)

5.2. Cost Comments and Caveats

- The standard Team X procedure is the Team X subsystems leads are responsible for the recurring and non-recurring costs of their design using parametric cost models. The costs in this study are rough estimates since it is outside the scope of the Team X costs models (which are based on space-qualified parts and space missions) and a more conservative approach has been taken.
- JPL typically holds a project level cost reserve (30% for concept, formulation, and development costs and 15% for operations costs), which have not been included in this study.
- The customer provided Launch Vehicle costs for the Terrier-Orion and Black Brant. The customer stated that the ground station and tracking costs are included in the launch vehicle quotes.
- Each of the cases was treated as a new-start mission. There is no cost benefit from non-recurring costs between the Cases. (Case 2 does not benefit from not paying the non-recurring costs of Case 1). This is due to the fact that the missions are different (size of parachute, guidance system, final descent stage, instrument suite, size of subsystems) and an exact copy is not being built.
- The customer provided cost inputs for the large parachute system (Case 1). Since the parachute size increases significantly, a ratio of cost to diameter was taken to estimate the materials costs for Cases 2 and 3.
  - Case 1: 80m diameter = $400K
  - Case 2: 130m diameter = (130/80)*(400) = $650K
  - Case 3: 200m diameter = (200/80)*(400) = $1000K

- The Final Descent Stage cost was also provided by the customer. Case 3 is approximately twice the mass of Case 2, and so an estimated increase in cost is 2:1. The cost for Case 2 was given as $200K; an estimate for Case 3 is $400K.
- The Team X design team completed costs for the Gondola in Case 1. The subsystems did not complete a cost estimate for Cases 2 and 3. The Gondola costs for Cases 2 and 3 are the same as Case 1; a more detailed look at the costs should be done at a later time.
    - Additionally, a full suite of subsystem engineers were not available during the design sessions, and so an estimate of costs for Command and Data Handling (C&DH), Telecom and Ground Data System (GDS), and Thermal were made without subsystem expert input to these three areas.

5.3. Cost Conclusions and Recommendations

The total project costs summary and details for each Case are listed in Tables 1 through 6.

- The project costs for each Case are intended as costs associated with a certain phase of the Megachute Program. Case 1 is the first phase of the program, Case 2 is the second phase, and Case 3 is the fourth stage of the program. Each Case is costed separately and includes the life-time costs of the Case.
- For each Case, a majority of the costs are launch vehicle, gondola, and the large parachute system. In order to lower the costs, reductions in size/cost would need to be made in these three areas.
    - Case 1
        - 15% of the total project cost is due to the launch vehicle
        - 21% of the total project cost is the gondola
        - 21% of the total project cost is the large parachute system
    - Case 2
        - 25% of the total project cost is due to the launch vehicle
        - 17% of the total project cost is the gondola
        - 22% of the total project cost is the large parachute system
    - Case 3
        - 19% of the total project cost is due to the launch vehicle
        - 13% of the total project cost is the gondola
        - 19% of the total project cost is the large parachute system

TABLE 21: TOTAL PROJECT COST SUMMARY CASE 1

CASE 1	FY05 $K
Maximum	10144
Expected	8454
Minimum	7608

TABLE 22: TOTAL PROJECT COST SUMMARY CASE 2

CASE 2	FY05 $K
Maximum	12508
Expected	10424
Minimum	9381

TABLE 23: TOTAL PROJECT COST SUMMARY CASE 3

CASE 3	FY05 $K
Maximum	16414
Expected	13679
Minimum	12311

TABLE 4: TOTAL PROJECT COSTS FOR CASE 1

Work Breakdown Structure (WBS)	FY05 $K Total Costs	FY05 $K Recurring Costs	FY05 $K Non-Recurring Costs	Comments
MegaChute - Case 1	**8454**	**6097**	**2359**	Mission is over 2 years. Total Cost is the first mission only.
Project Management	***1025***	***1025***	***0***	
Project Manager (PM)	450	450	0	Full-time PM for 1.5 years
Principal Investigator (PI)	450	450	0	Full-time PI for 1.5 years
Travel	100	100	0	Travel budget for the entire project
Meetings and Publications	25	25	0	Estimate
System Eng and Mission Assurance	***663***	***377***	***287***	
System Engineering	450	270	180	Full-time for 1.5 years
Mission Assurance	63	32	32	1 person for 3 months
Environmental Testing	150	75	75	Doesn't include Plumbrook costs
Science Team	***1125***	***1125***	***0***	
Science Team	750	750	0	5 part-time scientists
Science Data Analysis & Archiving	125	125	0	1 part-time person
Modeling	250	250	0	1 full-time person
Payload - Chemistry/Winds Payload	***3779***	***1968***	***1812***	
Instruments	***95***	***95***	***0***	
Temperature	5	5	0	
Pressure	5	5	0	
Extremely Low Frequency	75	75	0	
Radiometer	10	10	0	
Gondola	***1780***	***1068***	***712***	
Power	450	270	180	Battery, electronics, and labor
Structure	680	408	272	Structure, cabling, and labor
Attitude Control System (ACS)	400	240	160	LN200 IMU, GPS, and labor
Command and Data Handling (C&DH)	100	60	40	Estimate
Telecom and Ground Data System (GDS)	100	60	40	Estimate
Thermal	50	30	20	Estimate
Megachute System (Large Parachute system)	***1800***	***700***	***1100***	
Materials Development	100	0	100	Customer Provided
Materials	400	400	0	Customer Provided
Subscale Development	400	0	400	Customer Provided
Deployment Development	400	0	400	Customer Provided
Analysis	300	180	120	Customer Provided
Miscellaneous	200	120	80	Customer Provided
Final Descent System (Small Parachute system)	***0***	***0***	***0***	Not flown in 1st Option
Flight Approval (FAA)	***42***	***42***	***0***	1 person for 2 months
Payload Integration and Packaging	***63***	***63***	***0***	1 person for 3 months
Operations	***562***	***562***	***0***	
Ground Support	0	0	0	included in Launch Vehicle costs
Tracking	0	0	0	included in Launch Vehicle costs
Ocean Retrieval	62	62	0	1 person for 5 weeks; 3 days of 8 hrs at $1500 an hour
Operations Support staff	500	500	0	2 full-time people
Launch Vehicle	***1300***	***1040***	***260***	
Terrier Orion Vehicle 1	1300	1040	260	1st full-price launch

TABLE 5: TOTAL PROJECT COSTS FOR CASE 2

Work Breakdown Structure (WBS)	FY05 $K Total Costs	FY05 $K Recurring Costs	FY05 $K Non-Recurring Costs	Comments
MegaChute - Case 2	**10424**	**7647**	**2779**	Mission is over 2 years. Total Cost is 1st mission only.
Project Management	***1050***	***1050***	***0***	
Project Manager (PM)	450	450	0	Full-time PM for 1.5 years
Principal Investigator (PI)	450	450	0	Full-time PI for 1.5 years
Travel	125	125	0	Travel budget for the entire project
Meetings and Publications	25	25	0	Estimate
System Eng and Mission Assurance	***663***	***377***	***287***	
System Engineering	450	270	180	Full-time for 1.5 years
Mission Assurance	63	32	32	1 person for 3 months
Environmental Testing	150	75	75	Doesn't include Plumbrook costs
Science Team	***1125***	***1125***	***0***	
Science Team	750	750	0	5 part-time scientists
Science Data Analysis & Archiving	125	125	0	1 part-time person
Modeling	250	250	0	1 full-time person
Payload - Chemistry/Winds Payload	***4424***	***2453***	***1972***	
Instruments	***90***	***90***	***0***	
Temperature	5	5	0	
Pressure	5	5	0	
Extremely Low Frequency	5	5	0	
Radiometer	75	75	0	
Gondola	***1780***	***1068***	***712***	
Power	450	270	180	Battery, electronics, and labor
Structure	680	408	272	Structure, cabling, and labor
Attitude Control System (ACS)	400	240	160	LN200 IMU, GPS, and labor
Command and Data Handling (C&DH)	100	60	40	Estimate
Telecom and Ground Data System (GDS)	100	60	40	Estimate
Thermal	50	30	20	Estimate
Megachute System (Large Parachute system)	***2250***	***1070***	***1180***	
Materials Development	100	0	100	Customer Provided
Materials	650	650	0	Customer Provided with scaling
Subscale Development	400	0	400	Customer Provided
Deployment Development	400	0	400	Customer Provided
Analysis	300	180	120	Customer Provided
Guidance System	200	120	80	Customer Provided
Miscellaneous	200	120	80	Customer Provided
Final Descent System (Small Parachute system)	***200***	***120***	***80***	Customer Provided
Flight Approval (FAA)	***42***	***42***	***0***	1 person for 2 months
Payload Integration and Packaging	***63***	***63***	***0***	1 person for 3 months
Operations	***562***	***562***	***0***	
Ground Support	0	0	0	included in Launch Vehicle costs
Tracking	0	0	0	included in Launch Vehicle costs
Ocean Retrieval	62	62	0	1 person for 5 weeks; 3 days of 8 hrs at $1500 an hour
Operations Support staff	500	500	0	2 full-time people
Launch Vehicle	***2600***	***2080***	***520***	
Black Brant Vehicle 1	2600	2080	520	1st full-price launch

TABLE 6: TOTAL PROJECT COSTS FOR CASE 3

Work Breakdown Structure (WBS)	FY05 $K Total Costs	FY05 $K Recurring Costs	FY05 $K Non-Recurring Costs	Comments
MegaChute - Case 3	**13679**	**9352**	**2979**	Mission is over 3 years. Total Cost is 1st mission only.
Project Management	***1655***	***1055***	***0***	
Project Manager (PM)	750	450	0	Full-time PM for 2.5 years
Principal Investigator (PI)	750	450	0	Full-time PI for 2.5 years
Travel	125	125	0	Travel budget for the entire project
Meetings and Publications	30	30	0	Estimate
System Eng and Mission Assurance	***963***	***557***	***407***	
System Engineering	750	450	300	Full-time for 2.5 years
Mission Assurance	63	32	32	1 person for 3 months
Environmental Testing	150	75	75	Doesn't include Plumbrook costs
Science Team	***1875***	***1125***	***0***	
Science Team	1500	750	0	10 part-time scientists
Science Data Analysis & Archiving	125	125	0	1 part-time person
Modeling	250	250	0	1 full-time person
Payload - Noctilucent Layering Payload	***6024***	***3973***	***2052***	
Instruments	***1140***	***1140***	***0***	
Temperature	5	5	0	
Pressure	5	5	0	
Radar	50	50	0	
LIDAR	150	150	0	
UV-IR	400	400	0	
Laser Spectrometer	250	250	0	
High-Speed Camera	200	200	0	
Magnetometer	20	20	0	
TOF Mass Spectrometer	60	60	0	
Gondola	***1780***	***1068***	***712***	
Power	450	270	180	Battery, electronics, and labor
Structure	680	408	272	Structure, cabling, and labor
Attitude Control System (ACS)	400	240	160	LN200 IMU, GPS, and labor
Command and Data Handling (C&DH)	100	60	40	Estimate
Telecom and Ground Data System (GDS)	100	60	40	Estimate
Thermal	50	30	20	Estimate
Megachute System (Large Parachute system)	***2600***	***1420***	***1180***	
Materials Development	100	0	100	Customer Provided
Materials	1000	1000	0	Customer Provided with scaling
Subscale Development	400	0	400	Customer Provided
Deployment Development	400	0	400	Customer Provided
Analysis	300	180	120	Customer Provided
Guidance System	200	120	80	Customer Provided
Miscellaneous	200	120	80	Customer Provided
Final Descent System (Small Parachute system)	***400***	***240***	***160***	Customer Provided with scaling
Flight Approval (FAA)	***42***	***42***	***0***	1 person for 2 months
Payload Integration and Packaging	***63***	***63***	***0***	1 person for 3 months
Operations	***562***	***562***	***0***	
Ground Support	0	0	0	included in Launch Vehicle costs
Tracking	0	0	0	included in Launch Vehicle costs
Ocean Retrieval	62	62	0	1 person for 5 weeks; 3 days of 8 hrs at $1500 an hour
Operations Support staff	500	500	0	2 full-time people
Launch Vehicle	***2600***	***2080***	***520***	
Black Brant Vehicle 1	2600	2080	520	1st full-price launch